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GEOLOGICAL MAGAZINE

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Ptygmatic Structures and their Formation

By GILBERT WILSON

ABSTRACT

The conditions under which ptygmatic veins develop occur when the country-rock—as in a granitized area—is locally less competent or more yielding than quartzo-felspathic magma which may intrude it. Veins therefore which are being driven forward by pressure from behind, will buckle plastically if they encounter a resistance during injection, and a succession of such buckles will produce a typical ptygmatic vein. The amplitudes of the flexures so formed depend on the relative physical states of the vein and host-rock ; so for any particular vein there is usually a more or less constant size for the tortuosities developed. The mechanism explains several features observed in examples of ptygmatic veins, and has been reproduced experimentally in the laboratory. The contortions are therefore not necessarily due to the deformation of the veins by post-injection flowage or tectonic movements of the country-rock.

INTRODUCTION

THE term " ptygmatic " was originally coined by Sederholm in 1907 (p. 110) to describe " the primary folding caused by melting " in gneisses and migmatites. The word is derived from the Greek $\pi\tau\acute{\upsilon}\gamma\mu\alpha$ meaning " folded matter " ; and, as defined, would embrace most of the contortions, many of which are now included in the term " flow fold ", commonly seen in migmatite zones the world over. The original definition was, however, made " with every reservation ", and the term was later restricted by Sederholm (1926) to those tortuous quartzo-felspathic veins, which occur in areas of granitization, Text-fig. 1.

The phenomenon had been recorded previously, and the history of its investigation has been ably summarized by Kuenen (1938), who also conducted a series of experiments showing that analogous structures could be reproduced in the laboratory. Milch (1900) is credited with " the first clear description and discussion of these curious veins " ; he was followed by Sauer (1903), and then by Sederholm (1907 and 1913). Other descriptions and speculations as to the origins of these structures have been made by Holmquist (1920), Spurr (1923), Suter (1924), Read (1928, 1931), Ermannsdörffer (1938), Buddington (1939), Turner (1948), and Goguel (1948). " Pegmatite convolutions " showing typical ptygmatic vein structures were also observed by Andrews (1922–3, plates liv, lvi, lvii) at Broken Hill, N.S.W. ; and Odell

(1944, fig. 2) has illustrated a giant " ptygma " seen on a mountain side in Greenland.

There is a marked difference of opinion as to how these veins developed their remarkable form (Turner, 1948, p. 315 ; Kuenen, 1938). The majority of workers believed that they were originally planar structures and have, since their emplacement, been contorted either by mobilization of the host-rock during anatexis or granitization (Sederholm, Holmquist, and Ermannsdörffer), or by movements

TEXT-FIG. 1.—Ptygmatic vein of aplite in migmatite ; after Sederholm, 1926, fig. 34, p. 73.

resulting from externally applied tectonic forces (Milch, Sander, and Kuenen). The remaining investigators considered that in some way the folded forms of these veins were controlled by the physical conditions of the rocks at the place and time of their intrusion (Suter, Read, and Buddington). They believed that the field evidence forbade an appeal to post-intrusion movements or to external forces to account for the meander-like patterns.

The two divergent views regarding the formation of these structures can thus be summarized :—

(i) The foldings of the veins are *secondary*, and result from passive response to movements of the host-rock.

(ii) The folding is *primary*, and the tortuosities are the result of injection under special circumstances.

Such distinction becomes important when the folded structures are considered in relationship to the regional setting. If the origin of the ptygmatic veins is a secondary phenomenon it is related to the local rock-movements, and the structure has a tectonic significance. If on the other hand it is a primary injection phenomenon it is of no tectonic importance, but may yield a valuable clue to the local physical conditions of the rocks at the place and time of its formation.

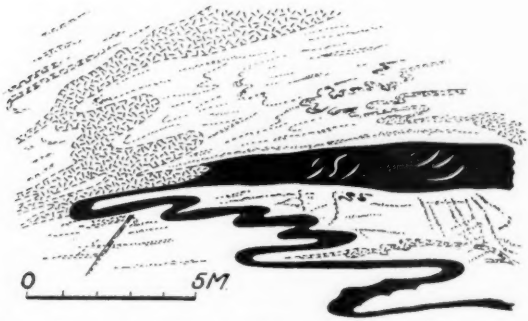
Ptygmatic Structures of Secondary Origin

The secondary origin of many of the complexly folded structures can be recognized in field examples, and has also been demonstrated by Kuenen's (1938) and Ermannsdörffer's (1938) experiments. Kuenen showed that the compression of a body of incompetent rock in which occurred a thin band of relatively competent material, such as an igneous vein or a bed of siliceous or calcareous sediment, resulted in a combination of plastic deformation or viscous flow and of intense folding. The incompetent material squeezed outwards in the direction of easiest relief ; the competent layer or vein crumpled, and presented a typical ptygmatic structure. The classic case of folding and the development of cleavage illustrated by Sorby (1853, p. 138) from Ilfracombe is an example of this mechanism, and the limestone band shown in his diagram closely corresponds in form with a ptygmatic vein. It is obvious that the bed was originally straight and planar, and was later folded ; and the cleavage which developed in the incompetent material indicates that the latter was subjected to an outward accommodational flow.

Geological literature contains many other similar examples : Geikie (1903, fig. 261) in his " Text Book of Geology " illustrated a small piece of Alpine limestone about 2 in. by 2 in., in which " puckering produced by great lateral compression " yielded contortions very similar to those seen in ptygmatic veins. Balk (1936, figs. 5, 8, 10, 11, 12, and particularly 13) showed several examples of crumpled siliceous beds and quartz-veins contained in more easily yielding pelitic schist : again the resemblance to ptygmatic veins can be seen. Goguel (1948, p. 307) considered the development of ptygmatic folds to be similar in principle to the folding of a competent bed surrounded by incompetent material. Any differences were merely a matter of scale. He cited the typical case of aplitic veins in gneiss where " during the compression of the rock-mass which gave rise to the production of the gneiss, the aplite played the part of a more resistant body, and was folded instead of participating in the deformation of the gneiss " (translation). Reference was made to an illustration in Demay (1942, pl. v, fig. 19). An even better example is the " Giant Ptygmatic Injection " of Ice Fjord, Greenland (Odell, 1944, fig. 2, p. 228) in which " the foliation (gneissic

structure) of the host rock appears to conform to the plications of the " ptygma ". It seems possible, however, that the buckling of the main structure and the development of secondary shear-planes and cross-fractures may at least in part be due to Caledonian movement ". Goguel (loc. cit.) also pointed out that analogous structures were formed by the folding of sediments. He referred particularly to an example from the Alpilles (Boûches-du-Rhône) where a bed of limestone lying between two thick groups of marl has been compressed and tightly folded upon itself.

The attenuation, folding, and rupture of basic dykes in the granitized areas and among the palingenetic granites of Finland illustrate the importance of host-rock movements in the formation of secondary structures (Sederholm, 1926). The fact that the dykes are in most cases fractured shows that they were too brittle to yield plastically. Examples



TEXT-FIG. 2.—Veins of metabasalt and pegmatite folded by host-rock movements ; after Sederholm, 1926, fig. 31, p. 71.

pictured on p. 71 of Sederholm's paper and reproduced here in Text-fig. 2, however, demonstrate the manner in which such intrusions can be folded by this mechanism.

In each of the examples discussed above the fold structures observed in the field are very similar to those obtained by Kuenen experimentally. They can be accepted as resulting from " the compression of plastic veins [or beds, G. W.] embedded in more ductile country-rock " (Kuenen, 1938, p. 26). Folds such as these may be related to the local tectonic pattern, and where sediments are plicated the contortions are usually concordant with the major structure. This is sometimes found among the folded veins, but more commonly there is " a general lack of uniformity in trend of associated fold axes, even within the field of a single large specimen " (Turner, 1948, p. 315). Where the folds are the result of folding by externally applied forces they should be expected

to conform to the local movement picture, and they can legitimately be used to measure crustal shortening ; but, if the contortions have resulted from some other mechanism, then their tectonic significance and their value as an estimate of deformation come under considerable suspicion.

Ptygmatic Structures of Primary Origin

Despite the support which is given to the " Secondary " or " Compressive " origin of ptygmatic folds by field and experimental evidence, examples are recognized where the contortions could not have been caused by such mechanisms, particularly those structures described by Read (1928, 1931) and by Suter (1924). The field sketches drawn by Read show tortuous veins intimately associated with straight unfolded veins, *all of the same age*, a fact which rules out the possibility of appealing to regional compression or to movements of the host-rock to explain the contortions. The example taken from Sederholm's works and shown here as Text-fig. 1, illustrates a ptygmatic vein cutting across an earlier unfolded dyke. This association fails to support the theory that the folding was caused by flow of the country-rock or by externally applied forces. Rather it seems evident that the veins themselves have been responsible for their own accordion-like crumpling, and ptygmatic structures must in many cases be primary.

(i) *Geological Environment of Ptygmatic Veins*

It is, at this point, worth considering the conditions existing in the rocks involved at the place and time when the ptygmatic veins were emplaced :—

(1) The veins are characteristic of injection complexes and regions of granitization.

(2) The veins are dominantly quartzo-felspathic in composition.

(3) The amplitudes and wave-lengths of the meander-like tortuosities are locally remarkably constant, but the same vein may be straight in one place and tortuous in another.

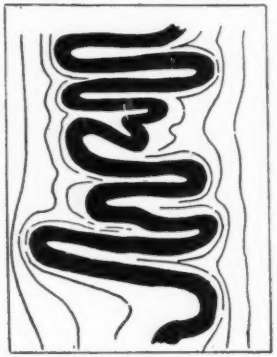
(4) Neighbouring veins may show little or no structural relationship to each other ; each vein seems to have its own individual fold direction and fold character.

(5) The vein texture shows no cataclastic structure (Sederholm, 1936, fig. 4 ; Read, 1928, p. 74). Either the veins solidified after folding, or their present fabric is the result of recrystallization and annealing (Sander, 1914).

(6) " The wall-rock is intensely deformed close to the vein, but much less at a very short distance away from it " (Kuenen, 1938, p. 17). Kuenen's diagram (3 D, I, after Milch) illustrating this point is reproduced here in Text-fig. 3.

(7) Kuenen, Milch, and Sander considered that when the veins were contorted they were plastic, but embedded in more ductile country rock. Read, however (1928, p. 76), stated that " there is no evidence that the veined Moine sediments were ever in a softened or semi-molten condition."

This last opinion of Read's was criticized by Kuenen (1938, p. 22), and it also opens up an immense field for speculation : what were the conditions in the rocks at such a time ? What is understood by " softened ", " semi-molten ", and suchlike terms in respect to rocks at plutonic depths as are at present being considered ? On the earth's surface most rocks are more or less brittle, but under high retaining pressures they can be deformed by creep without rupture ; they behave as if ductile or plastic in their responses to applied forces which, under near surface conditions, would cause them to break.



TEXT-FIG. 3.—Ptygmatic vein, after Milch (1900) ; from Kuenen, 1938, fig. 3, D, 1 ; p. 16.

The behaviour of magma at depth, however, appears to be the complete antithesis of that of the country-rock. " Magma " is commonly considered to be something in the nature of a " liquid that finally consolidates as rock " (*Encyc. Brit.*), or " molten rock material highly charged with gases " (Holmes, 1944, p. 28). Nearly all definitions include the idea of fluidity and suggest to the reader that even at depth magma may have the physical properties of porridge.

The vulcanological and geophysical studies carried out on Kilauea in Hawaii have shown that this conception is probably far from the truth. The fluidity of lava, bubbling and eddying in the great lava lake, due to superheat from gas reactions at or near its surface, is misleading. " The ' lava column ' in the depths . . . is judged by Jaggar to consist of *relatively very immobile* ' hypomagma ' with ' reagent gases in solution ' . . . " (Cotton, 1944, p. 10 ; Jaggar, 1920, p. 273). At depth and with increase in retaining pressure the magmatic fluids tend to become more rigid, or rather their viscosity is greatly increased : while the solid country-rocks lose their brittleness and become more and more plastic. A convergence in physical characters seems to occur under plutonic conditions.

Whether or not magmas at depth reflect the same differences in viscosity due to differences in chemical composition as do lavas at the

surface cannot of course be stated. It is well known that whereas a basic lava will flow readily and easily, acid lavas are viscous, even though they melt at lower temperatures. For a given temperature therefore, a quartzo-felspathic magmatic " melt " at depth may quite conceivably have a viscosity of the same order of magnitude as the ductility or plasticity of the contiguous country-rocks. In a region undergoing granitization or similar processes, conditions in the rocks are found to be variable from place to place and from time to time. Variations in the temperature and in the chemistry of the country-rocks will be reflected in variations in their strength, rigidity, plasticity, etc. In some places, therefore, they may have become relatively softened or capable of behaving as very plastic or even viscous material without necessarily having become " semi-molten ". This conception closely agrees with that proposed by Sander (1914) and discussed by Kuenen (1938, p. 23). It is into such physically heterogeneous rocks that I picture those quartzo-felspathic dykes which developed ptygmatic structures being injected.

(ii) *The Mechanism of Ptygmatic Injection*

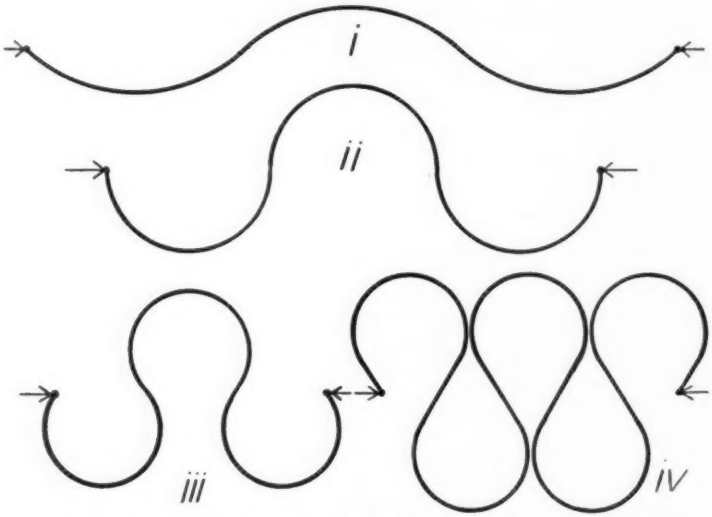
A vein, which in one place was moving between relatively solid confining walls, may, in a region undergoing granitization, and because of the local conditions, suddenly find itself entering and penetrating *a country-rock which was more mobile (less rigid) than the intrusion itself.* The vein, rigidly guided by the solid walls (*S* in Text-fig. 5) would then be forced forward through the more ductile host-rock (*H*), as a thin plastic sheet, due to the *vis a tergo*. Under ideal conditions the leading edge of the sheet would cut through the softer rock as a knife goes through butter. The lateral restraining effect of the surrounding but incompetent host-rock will keep the vein following its leading edge in the original plane or around gentle curves, but not around abrupt bends. Solidification at this stage would result in straight, winding or curved veins, but would not account for the tortuosities to which the term ptygmatic is usually applied.

If, however, the moving sheet were to encounter some resistance (*R* in Text-fig. 5) on the far side of the soft zone of rock, its power to penetrate this obstacle would depend upon its own strength and ability to transmit a sufficient force from behind to its forward or cutting edge. Where the injected sheet is held between solid walls this force is transmitted by hydrostatic pressure ; but within the relatively soft or viscous zone the firm rigid support of the walls is absent and the sheet behaves like a strut.

Its ability to transmit a force thus depends on its own power to resist buckling. The theoretical behaviour of the injected vein can therefore be examined as if it were a thin strut or flat rod fixed at

one or both ends, encased in a yielding medium, and subjected to a compressive load.

The shape assumed by a thin elastic strut when it is buckled by a compressive force applied at the ends and acting parallel to its original length is well known in mechanics, and is termed the *Elastica* (Love, 1893, vol. ii, pp. 47–52), Text-fig. 4, i–iv. With the application of this force, as shown by the arrows, the rod is first gently and then more and more strongly flexed until the curves that are formed touch each



TEXT-FIG. 4.—The development of the "Elastica"; after Love (1893), vol. ii, figs. 32–5.

other. As far as we are concerned Text-fig. 4, iv, is a limiting case, but it and the preceding diagram might present idealized sections of ptygmatic structures. These ideal continuous curves are, however, only first approximations, because here we are not dealing with an elastic material, but with a plastic one. The curve produced by the deformation of a plastic strut has recently been investigated by W. P. Cashmore in the Mechanical Engineering Department of the City and Guilds College of the Imperial College. Cashmore found that when a thin rod was compressed as a strut with pin-jointed ends, and by suitably choosing the dimensions and material of the rod, it tended, after an initial elastic deflection in the form of a continuous curve throughout its length to yield by bending abruptly in the region of greatest bending moment. Further plastic yielding was confined to

this region, the exact configuration of the flexure being dependent on the work-hardening properties of the material of the rod.[1] This ultimately resulted in a hairpin-like structure with straight limbs on either side of a sharp flexure [2] and the curve developed has been named the *Plastica*. This closely approaches the characteristic form found in the individual folds of most ptygmatic veins (see in particular Text-figs. 1 and 3, and Read, 1931, Fig. 6, p. 110), as well as in many common bedding flexures. Unlike the elastica, whose flexing is continuously controlled by the elastic stresses throughout the length of the strut, the plastica is actively deformed around the point of maximum curvature only, and its limbs close passively. If, however, the plastic strut be encased in a yielding medium which is slightly less rigid than the strut itself, a uniform restraint countering its tendency to buckle on a large scale will be active over its whole length, and small-scale deflection necessitating only local displacement of the surrounding medium will alone be possible. Once a fold has developed to the limit imposed by the existing conditions of restraint, a second bend curved in the opposite sense will form to accommodate the compressive yield, only to close up in turn, and to give way to the formation of a third fold . . . and so on. A buckle which has closed to the limit permitted by the surrounding material becomes dead, and if the compressive force is still being exerted a new one must form to give the necessary relief. In each case the stresses which are active within the vein and in the surrounding material are approximately uniform, so there will be a general constancy of fold amplitude and wave-length over any one section of any particular vein.

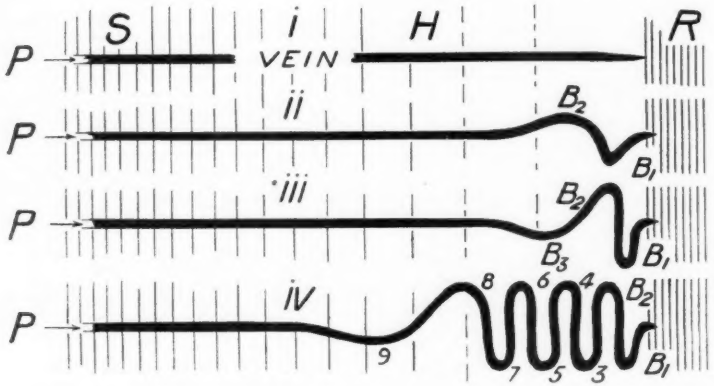
The theoretical development of ptygmatic structure from the plastica is shown in Text-fig. 5, i to iv. The vein (solid black), having been moving between walls more rigid than itself, has traversed a zone of country-rock which due to granitizing agents is more yielding or less viscous than the vein matter itself. The change from rigid to soft country-rock will probably be gradual. The restraining influence which is exerted on the vein will thus diminish from the left-hand side of the diagram and its degree is indicated in the figure by the spacing of the ornament. The vein is shown to have encountered a resistance (R) on the right-hand side of the viscous zone, which impedes its further progress. Despite this obstacle the vein is still being forcibly fed forwards by the pressure P so that it eventually buckles at, say, B_1, where the size of the buckle will be directly proportional to the difference in strength between the vein and the less resistant host-rock. The formation of the fold will allow the vein as a whole to slip forward

[1] Personal communication from Professor Hugh Ford.

[2] The structure can be demonstrated by the buckling of a thin strip of plasticine, or even of a pipe-cleaner.

(to the right), but only the host-rock *in the immediate vicinity of the actual buckle* will be affected by the contortion (see p. 5, paragraph No. 6). Because the vein matter is plastic the fold developed will show a sharp curvature and straight limbs, Text-fig. 5, iii, similar in form to the normal plastica.

The buckling of the vein in one direction will cause it to bend in the opposite sense if the longitudinal pressure is continued, Text-fig. 5, iii. Other folds, similar in shape to B_1, and subject to the same controls



TEXT-FIG. 5.—The development of a ptygmatic vein as the result of plastic buckling during injection.

P = Magmatic pressure driving the vein forwards.
S = Solid country-rock.
H = Viscous or plastic host-rock.
R = Resistance of solid rock.
B_1, B_2 = Plastic bucklings of the vein in the theoretical order of their formation.

will thus be produced, and the process will continue with the development of a series of small plastica-type tortuosities, B_2, B_3, etc. In this way the ptygmatic structure tends to grow up-stream along the vein while the body of the vein is fed forward step by step as each successive buckle forms and closes (Text-fig. 5, iv). In this last diagram the actual length of vein shown is approximately double that in Text-fig. 5, i; this is the result of the forward movement of the vein accommodated by the folding.

The amplitudes and wave-lengths of the folds will depend upon the amount of deflection permitted to the vein by the yielding host-rock which has to be displaced to allow for the folding. This displaced material will be pressed outwards at convexities, but will be nipped in between successive buckles, and will thus separate adjacent

" meanders " ; beyond the width of the " meander belt " the country-rocks will be but little affected. Kuenen's line drawing of Milch's ptygmatic vein (shown in Text-fig. 3) illustrates the theory proposed here perfectly, provided it is understood that the forces responsible acted along and within the vein alone and not in a general vice-like compression of the vein and of the country-rock.

(iii) *Experimental Evidence*

The theory of the development of ptygmatic structures, outlined in the section above, receives considerable support from small-scale experiments. After tests with various media had been made, it was found that structures simulating those observed in the rocks could be produced by injecting a thin ribbon of putty into a soft jelly made from ordinary cooking gelatine.

The apparatus used consisted of a glass-sided tank 30 cm. long × 23 cm. high × 7½ cm. wide, and having a volume of approximately 5 litres. Cool, but liquid gelatine solution was poured into this tank and allowed to set. The material (in this case putty) which was to be injected into the jelly was loaded into a steel tube 30 cm. long and having an internal diameter of 2 cm. One end of this tube had been flattened into a fish-tailed nozzle approximately 3 cm. × 0·35 cm. The tube was securely clamped into position with the nozzle penetrating the jelly of the tank for about 1 to 2 cm. The putty was then forced through the nozzle into the jelly by pressure exerted on a plunger in the tube.

The results obtained varied with the relative consistencies of the putty and the jelly. This relationship was easily modified by varying the amount of gelatine dissolved in the 5 litres of liquid used in each experiment. There appear to be four important relative strengths of the two materials :—

(1) The host is much more rigid than the injected material.

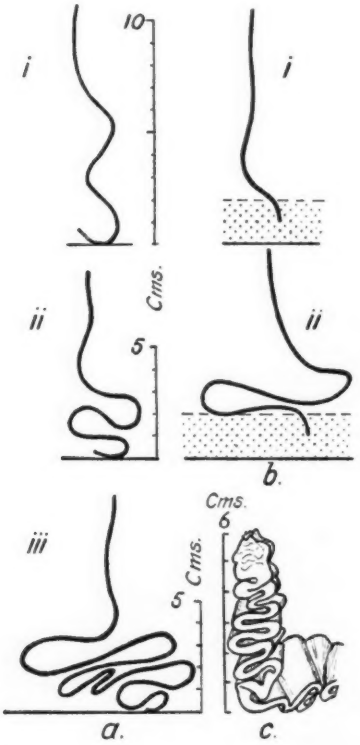
(2) The host is very slightly firmer than the injected material.

(3) The host is slightly weaker or more yielding than the injected material.

(4) The host is relatively fluid when compared with the injected material.

Case 1 was not actually investigated experimentally as its conditions represent those usually found among minor injected bodies, dykes, etc. Here the fluid magma is known to have forced its way along fractures in the rigid country-rock, and the solid walls of the fissures control the form of the intrusions. That the advancing magma is capable of wedging open a path for itself between rock-walls has been clearly demonstrated by E. M. Anderson (1942, p. 23).

In Case 2, where the injected material was but a little more fluid than the host, the ribbon of putty balled up into irregular convoluted lumps as it left the rigid support of the tube. The bodies showed no evidence of structural control in their rounded shapes, and were the product of an intrusion and a host which, though immiscible, possessed



TEXT-FIG. 6.

Ptygmatic structures developed experimentally by injecting a ribbon of putty into soft gelatine, *a* and *b* drawn from photographs.

a i, ii, iii. Three stages in the development of ptygmatic structures formed as the vein, injected from above, encounters a solid resistance. The folds in (iii) have partly collapsed because of the weight of the putty and the softness of the gelatine.

b i and ii. (i) The vein has penetrated a resistant layer of gelatine (stippled) at the base of the tank, and an initial kink has developed, cf. Fig. 5, ii. (ii) As injection proceeds the kink develops into a complete fold, while a second plastica type flexure forms above, cf. Fig. 5, iii.

c. Sketch of a ptygmatic vein developed experimentally. The lower part of the structure collapsed and slipped sideways along the bottom of the tank during the experiment.

approximately the same viscosity or plasticity. Analogous bodies occur in nature in the form of pegmatitic, aplitic, or quartzose nodes and irregular masses. Such masses may be sheared off from their original feeding channels by only slight movement of the containing rock, with the result that the acid intrusions appear as lone segregations. Some specimens of the Kennack gneisses of the Lizard, Cornwall, and the indeterminately shaped body of pegmatite on the right-hand side of Text-fig. 1, were probably formed under such conditions.

Case 3 was of particular interest in this investigation because the conditions were similar to those proposed and discussed as necessary to the production of ptygmatic structures. As the putty ribbon was squeezed through its orifice into the jelly it cut its way through the latter with but slight deflection. The ribbon was injected from above downwards, and at the bottom of the tank used was a layer of denser jelly (stippled in Text-fig. 6, *b*). The ribbon penetrated this layer for a small distance and then, as the rate of intrusion was maintained, developed a kink at its lower end—compare Text-fig. 6, *b*, i, with Text.fig. 5, i. The initial kink then evolved into a typical plastica fold, Text-fig. 6, *a*, ii ; 6, *b*, ii, and with further intrusion of the ribbon more folds formed one above the other in turn, Text-fig. 6, *c*. The structures produced and illustrated in Text-fig. 6 are closely comparable with typical ptygmatic veins and their development was in complete accord with the theory proposed above.

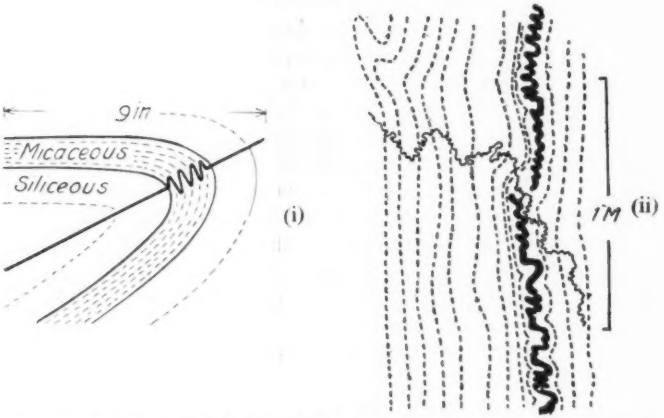
Case 4 yielded results very similar to those obtained in Case 3. The putty ribbon cut easily through the liquid jelly and an initial kink formed near the contact with the stiffer material. The kink then developed into a plastica-type fold, but the amount of the vein involved in the deflection was much greater than in Case 3. This first fold and those which developed subsequently have in consequence relatively large amplitudes because of the weaker external restraint. Also, the folds of heavy putty tended to settle down on one another owing to lack of support and thus packed tightly together. This occurred to a certain extent in Text-fig. 6, *a*, iii.

(iv) *Discussion of Some Field Examples*

The theory of the formation of ptygmatic veins outlined in the foregoing pages readily explains many of the structures observed in nature. An interesting case is that described by Read (1928, Fig. 2 H), shown here in Text-fig. 7, i, in which a vein lying along the axial plane of a fold passed from siliceous Moine granulite through a layer of pelitic schist into another bed of granulite. The vein was straight in both the granulites, and ptygmatic in the intervening schist. The vein while in the granulites was controlled by them, and initially it must have penetrated straight across the schistose layer. If during the injection of the vein resistance to its forward movement occurred, even outside the area seen in the exposure, the force responsible for the intrusion would still be active, and would still be trying to push the vein on through the rock. That part of the vein lying between walls of solid rock would be held rigidly, and there its planar form would be maintained. The vein, however, yielded ptygmatically where it passed through the mica schist and so permitted the rear portion of the vein to slip forward to relieve the otherwise confined hydrostatic

force behind. This folding could only occur if the vein were able to force the schistose material aside laterally, which means that the schist must at the time have been more yielding than the material injected. The apex of a fold is usually the locus of influx of incompetent material ; it is therefore highly improbable that the ptygmatic contortions in this case could have been produced by crumpling associated with the folding of the country-rocks, or with any outward migration of the softer pelitic schist.

Kuenen (1938, fig. 2 A) illustrated an example shown here in Text-fig. 7, ii, of a ptygmatic vein which is confined to a particular

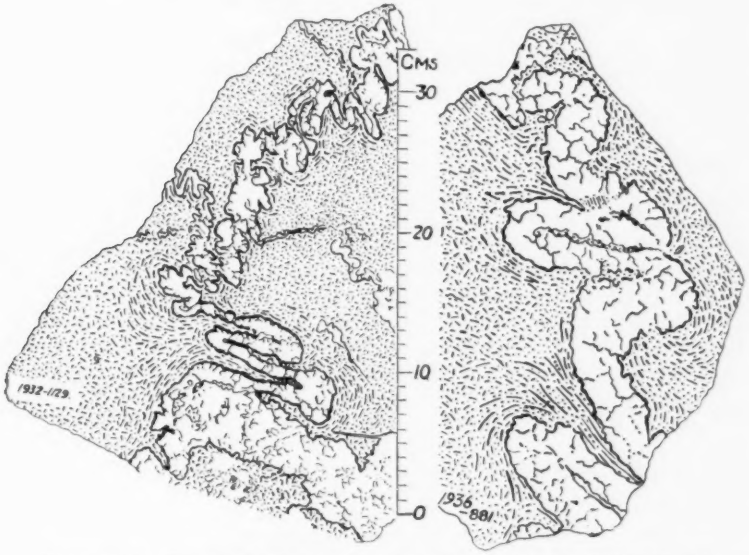


TEXT-FIG. 7.—(i) Ptygmatic structure in a vein confined to a particular rock-type ; after Read, 1931, Fig. 7, H.
(ii) Ptygmatic vein lying parallel to the foliation of an unfolded host-rock ; after Kuenen, 1938, Fig. 2, A.

layer in the country-rock. Both are cut by a thinner ptygmatic vein which fails completely to show any structural correspondence with either the host-rock or the main vein. The flexures in neither vein suggest their formation by external compression, and it is obvious that the folding of the main vein by such agencies without corresponding crumpling of the foliation planes in the country-rock was impossible. The tortuosities must have been intimately related to the actual injection of the vein itself. The example is of additional interest because it illustrates a case where the fold amplitude appears to be controlled, at least partly, by the pre-existing structure in the host-rock. The structure in this example is closely comparable with that illustrated by Milch (1900), Kuenen (1938, fig. 3, D 1), and given here in Text-fig. 3.

Two examples of ptygmatic veins from Finland are shown in Text-

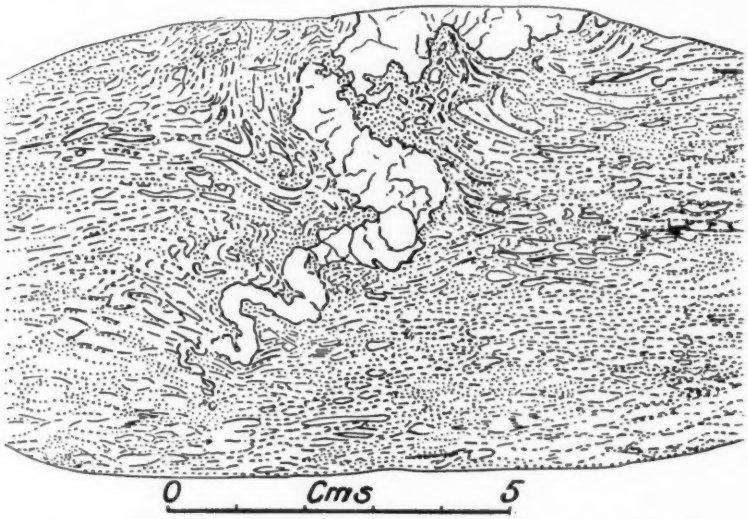
fig. 8, i and ii. The drawings were made from specimens (B.M. 1932—1129 and B.M. 1936—881) of the Mineral Department of the British Museum (Natural History), London, S.W. 7. The specimens were presented by the Geological Society of Finland, and are polished slabs of rock from Itamerenkatu, Helsinki–Östersjögatn ; both are described as " migmatite with ptygmatic veins ". The migmatite is a grey dioritic rock which on the polished surface appears almost black flecked by sporadic pink felspars. There is no megascopic directional (platy or



TEXT-FIG. 8.—Ptygmatic veins in migmatite. Specimens B.M. 1932/1129 and 1936/881, from the Department of Mineralogy, British Museum (Natural History).

linear) structure in the rock, but the pink quartzo-felspathic ptygmatic veins present typical plastica-type flexures in both cases. The formation of these flexures has locally forced the fabric of the country-rock into conformity with the vein margins. This fabric orientation—illustrated by the ornament in the diagram—disappears into the general homogeneous structure of the migmatite at a small distance from the vein. The absence of any oriented macroscopic fabric in the mass of the migmatite shows that the rocks as a whole had not been subjected to any significant directed pressure ; but the local conformity of the host-rock fabric to the curves and margins of the folded veins indicates that the tortuosities had a primary origin.

The effects of ptygmatic veins penetrating rock which has a pronounced foliation are shown in Text-fig. 9. The specimen illustrated is a boulder whose original source is not known, collected from Nigg Bay, Aberdeen, by Drs. John Sutton and Janet Watson. The rock consists of fine-grained mica gneiss of which the foliation is parallel to the long axis of the specimen, and is normal to the polished surface shown in the figure. This foliation is not parallel to the fold axial-planes of the ptygmatic veins, except where it has been pinched in between concave bends. It is deflected around convex bends so that it becomes sub-

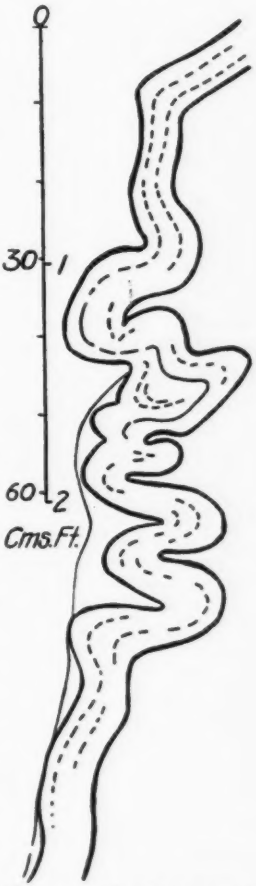


TEXT-FIG. 9.—Distortion of the foliation of a gneiss resulting from the development of ptygmatic structure in an injected vein. Boulder from Nigg Bay, Aberdeen ; Imperial College, S.W. 7, collection.

parallel to the edges of the vein. The gneissose fabric is deformed by the folding of, and in the neighbourhood of, the vein only ; and there is no evidence that the deformation responsible for the development of the gneissose structure was also the cause of the ptygmatic contortions of the vein. Rather it appears that the injection of the vein was post-tectonic, and the folding must therefore be considered primary.

This destruction of original planar rock-fabric, and its local deflection into more or less conformity with the flexures of the ptygmatic veins has been specially accentuated, because it permits distinction between tectonic and non-tectonic folding of the veins. Where competent and incompetent layers have been compressed together, at

depth in the earth's crust, the former are folded, while the latter flowing outwards become cleaved or schistose. As the schistosity and the folding are the product of the same movement they are intimately related, and the planar structure is *not* broken down in the vicinity of the folded layers. In fact, it not only persists up to the margins of the more competent bands, but may even continue across them. Examples of such relationship are legion, e.g. Balk (1936, figs. 7, 8, 10, 11), Sorby (1853, p. 138), Geikie (1903, figs. 270, 272), etc. Where, however, a vein shows intense crumpling which is non-accordant with the host-rock structure, or which even tends to break it down, one is forced to the conclusion that the folds were later than the movements responsible for the country-rock fabric, and resulted from conditions during injection.



TEXT-FIG. 10.—Ptygmatic structure developed in the siliceous core of a calcsilicate band in Moine Schists, Ross of Mull, Mull, Argyll.

An unusual example of a sedimentary ptygmatic structure is shown in Text-fig. 10. The contorted rock forms the more siliceous core of a calc-silicate band in pelitic mica-schist in the Moine Series of the Ross of Mull. The band as whole is conformable with the steeply dipping bedding of the schists; but the folding of the core is disharmonic, and its style in no way corresponds with that of the local tectonic structures, all of which have a regular, markedly monoclinic form of symmetry. The ptygmatic crumpling is the result of plastic folding of the core alone; it is due to a longitudinal compression, and not to drag-folding developed by bedding-plane slip during a tectonic movement. The siliceous layer was evidently pushed against a resistance, and while it folded on itself it became unstuck (*décollé*) from the more calcareous rock on either side. This latter material moulded itself to the curves of the

contorted strip, and at the same time, because of its limited mobility in a confined space, controlled the extent to which the plastic folding could develop.

Conclusions

The object of this paper is to demonstrate that ptygmatic structures can develop in veins during and as a result of their injection. Experiments and theoretical considerations show that this is mechanically possible provided certain physical relationships between the host-rock and the injected material are present. There is no necessity to appeal to externally applied forces or movements of country-rock to account for the formation of the vein tortuosities. The physical conditions requisite are that the country-rock, at the time and place of intrusion, was more mobile than the magmatic material of the veins themselves. The contortions were thus formed by plastic buckling of the vein due to magmatic pressure from behind, with the concomitant displacement of yielding contiguous host-rock. The ptygmatic structure is thus considered a primary phenomenon. Kuenen (1938) has also shown that intensely contorted veins may arise by post-intrusion deformation of the rocks as a whole under deep-seated conditions. The two mechanisms are, however, in no way mutually incompatible nor exclusive.

The contortions of primary ptygmatic veins formed in country-rocks which were static and which were not being tectonically deformed do not necessarily reflect the structure of the surrounding material. Examples are shown in Text-figs. 1, 3, 7, 8, and 9. The structural symmetry of the veins and their style of folding differ from that of the host in which they lie both in class and orientation. Kuenen (1938) in his experiments allowed the mobile host material to squeeze out symmetrically on either side of the more competent band which was being folded. In consequence the symmetry of the deformed band and of the host both tended to be more or less the same. In nature such symmetrical migration of material is highly improbable, except locally, but a one-way movement or shear in rocks is common. Response to such latter conditions will be reflected in the folding of the vein and in the deformation of the surrounding rocks, both of which would be expected to show accordant monoclinic structural symmetry. Veins whose contortions result from passive yielding to differential movements in the country-rocks may be expected to resemble drag-folds, and in their general appearance to simulate deformed thin competent beds as, for example, in Text-fig. 2. Primary ptygmatic structure in veins which were injected into a host-rock that was at the same time moving will also show monoclinic symmetry. The vein tortuosities will be pushed over laterally along the planes of movement ; they would,

as it were, curve with the current. Such a combination of circumstances might account for the deflected ptygmatic veins illustrated by Spurr (1923, figs. 35 and 36, p. 166).

The granitization of a region is often later than the orogeny responsible for its folding, consequently any rock movements that do occur within the complex during its metasomatism may result from purely local adjustments of little tectonic importance, or they may be guided by the earlier tectonic pattern. Similarly ptygmatic veins in granitized terrains may or may not reflect the large-scale movements. Ptygmatic veins can thus be classified into three structural groups :—

(1) Veins of which the contortions result from primary buckling during injection into static country-rock, and so have no tectonic significance.

(2) Veins whose contortions are the product of combined primary injection and country-rock movement. The structural symmetry of these veins will reflect the local deformation which may or may not be in accord with the regional tectonic picture.

(3) Veins whose contortions agree with those of the country-rock.

(*a*) These veins may owe their shapes to injection after tectonic movements had ceased along planes of weakness formed by sharply plicated bedding or foliation planes in the country-rock : the injection is thus mimetic.

(*b*) They may have been contorted by post-injection movements as Kuenen has suggested.

(*c*) They may actually have been emplaced along the bedding-planes while the movement was in progress. Thus segregation veins in the apices of combined flexure- and shear-folds may, together with the bedding, be intensely contorted ; even so, owing to the mechanics of the deformation, the folds of such veins cannot be used to compute local crustal shortening.

Hence veins in which ptygmatic structures are developed may be post-, para-, or pre-tectonic in their emplacement. It is, however, only when the veins are undoubtedly pre-tectonic that their folding may be used—with any approach to justification—to estimate the amount of compression that the rocks have suffered, and even here care must be exercised.

The primary development of ptygmatic structures in veins can only occur under special physical conditions which were recognized by Kuenen, Milch, and Sander. They were also hinted at by Read (1928) when he considered that the structure only formed in rocks in which

plane fractures could not form, though it is difficult to accept his suggestion of intrusion along a tortuous initial fissure. Such rock can only be plastic or viscous in its behaviour, and its rigidity appears to be so small that it is actually more mobile than the local magmatic veins. Under these circumstances the country-rock is itself potentially intrusive. It might be expected to move if a passage were opened up for it ; or, were it subjected to some directed force, it would transmit the latter as hydrostatic pressure, and so might break its way upwards as an intrusive stock or diapir. It is significant to notice that rocks can achieve this physical state and still retain many of their diagnostic sedimentary features, as in Central Sutherland (Read, 1931). Ptygmatic veining can thus be used as an indicator of the physical state of the injected country-rocks or of their potential mobility at the time when the veins were formed.

Read (1928, p. 77) considered " The term ' ptygmatic folding ' denotes that the user believes that veins showing this folding were originally straight ; the term should be limited to such cases ". I should like to modify this suggestion and restrict the term to those highly contorted structures which owe their form to externally applied forces or to passive yielding to host-rock movements, which latter would include Sederholm's " primary folding caused by melting ". That is, to the secondary class of structures discussed in this paper. For those other even more tortuous veins of primary origin, which might be said to be ptygmatic " in their own right ", and owe their form to their own injection processes, the term *Ptygmatic Injections* is proposed. It describes the form and origin of a typical and significant plutonic structure, and unlike " ptygmatic folding ", it is not tautological.

The author gratefully acknowledges the assistance and constructive criticisms of Professors H. H. Read, F.R.S., and Hugh Ford (Professor of Applied Mechanics in the City and Guilds College, London, S.W. 7) in preparing this paper. He is also indebted to Professor Francis Turner, and Drs. John Sutton and Janet Watson for reading the typescript and contributing helpful suggestions. Assistance in the construction of apparatus and in photographing the experiments was kindly given by Messrs. E. J. Hill and J. A. Gee respectively. Permission to reproduce the following Text-figures, Nos. 1 and 2 (Sederholm, 1926), Nos. 3 and 7, ii (Kuenen, 1938), and No. 7, i (Read, 1928, 1931), was kindly given by Dr. A. Laitakari on behalf of the Commission géologique de Finlande and the Société géologique de Finlande, and by the Director of H.M. Geological Survey, to whom the author is duly appreciative.

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Cyclic Sedimentation of the Rough Rock (Millstone Grit) as illustrated by a section near Eakring, Nottinghamshire

By K. W. Bond

(PLATE I)

Abstract

The section described is a well section, 20 miles from the nearest Millstone Grit outcrop. Attention is drawn to the rhythmic sedimentation resulting from the intermittent subsidence that was occurring at the time.

Introduction

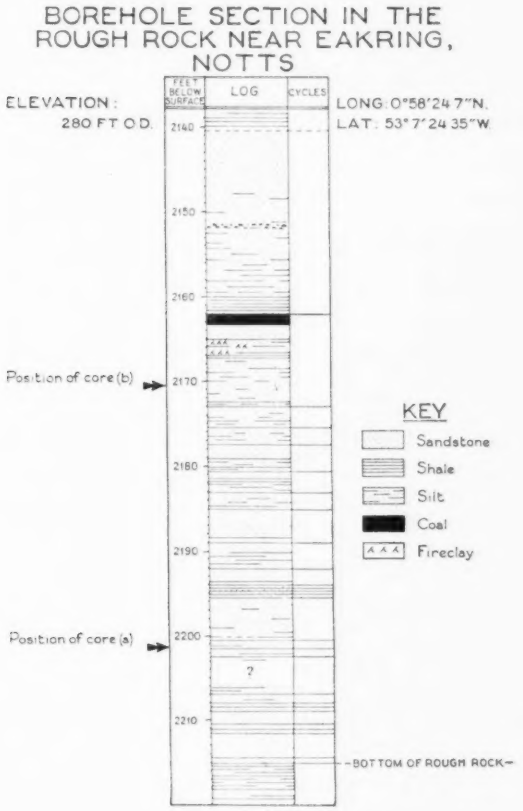
THE rhythmic sedimentation of the Coal Measures has received considerable attention because of its economic importance, but it can be shown (in suitable areas) that the effect is just as well marked in so uniform a formation as the Rough Rock. The following section (Text-fig. 1) was obtained during the drilling of a well on the east flank of the Duke's Wood Oilfield, near Eakring. Cores were taken of the entire Rough Rock succession with the exception of the initial three or four feet; recovery was so excellent that an almost complete section could be reconstructed. Acknowledgment is given to the Chairman and directors of the Anglo-Iranian Oil Co., Ltd., for permission to publish the facts contained in this paper.

Geology

In the Eakring area, the Rough Rock is much finer-grained and less felspathic than its equivalent farther north in Yorkshire, and lacks its noted uniformity of lithology and persistence of occurrence. The base is rather difficult to define and has been arbitrarily taken as the point where arenaceous beds become predominant over silts and shales in a mixed series. The top is more definite and is the junction between thick bedded brown sandstone below and black shales above. Throughout the 75 feet of sediments thus included, it is possible in this case to recognize not less than twenty-six cycles of deposition. They differ from the Coal Measure cycles or units in being mainly arenaceous and consist of thin shales, passing upwards into sandstone. In one instance the cycle is terminated by a coal seam.

Most frequently the junction between the cycles is a sudden change but occasionally it is more gradual. The lower cycles are thinner and show little deviation from the standard type (Text-fig. 2), while the most irregular cycle is that between 2,162 feet and 2,173 feet below the surface, and which appears to have been interrupted. Commencing with a normal shale band (6 inches), it is followed by slumped and contorted silts and sandy beds (5 ft. 6 in.) in which nodules of ironstone

and films of coal occur (Pl. I, Fig. (*b*)). Following this are unbedded silts (2 feet) resembling fireclay in parts, with rootlets and plant remains suggesting a seat-earth. Instead of this ending the cycle it is followed by a massive 2 feet sandstone indicating flooding and overwhelming



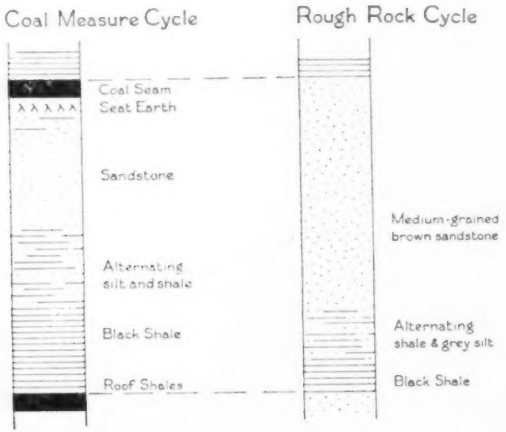
TEXT-FIG. 1.

of the swamp conditions before the next subsidence commenced. A thin 1-inch seat-earth overlies the sandstone in the normal way and underlies a 15 inches coal seam which completes the cycle.

The coal seam is a common occurrence in the Eakring succession and separating it and the Coal Measure shales, is the topmost and thickest cycle over 22 feet thick. Starting with shales, possibly marine,

it becomes a massive light brown sandstone through a series of silts and sandstones.

Thus in a rock group which is often called uniform we can trace



TEXT-FIG. 2.—Comparison between ideal Coal Measure and Rough Rock Cycles.

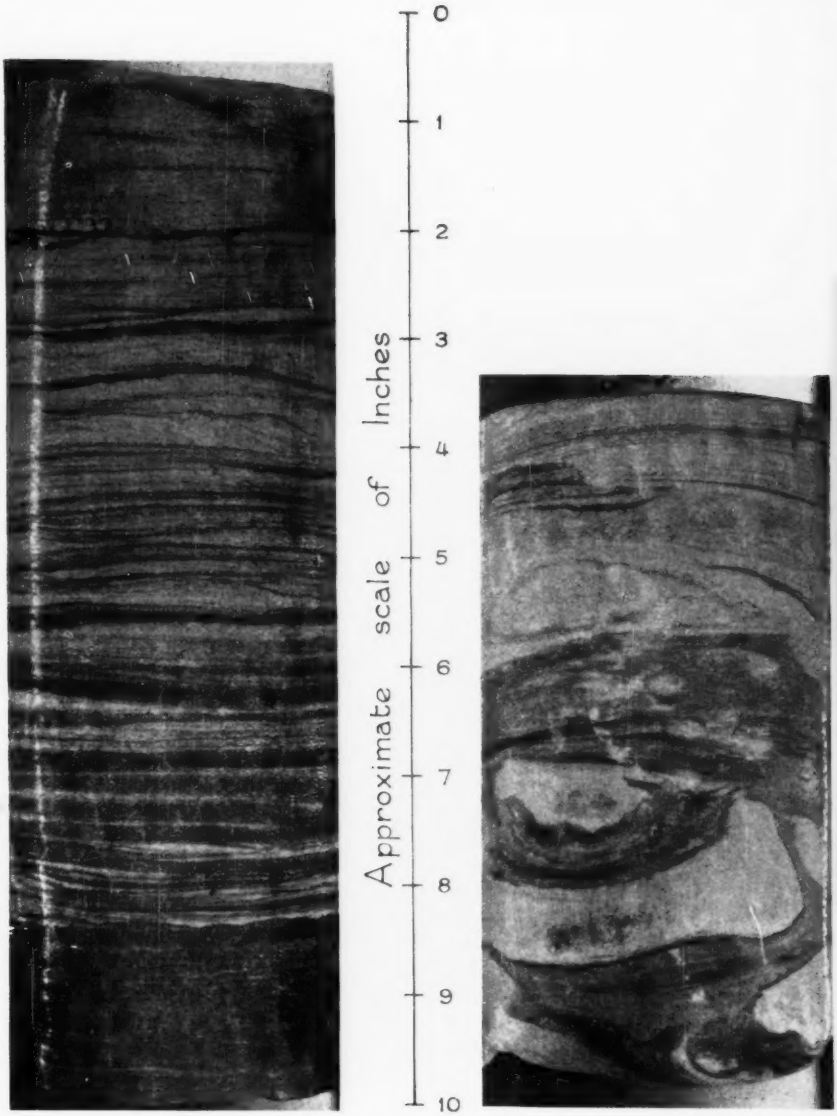
a series of small cycles acting within the major sedimentary cycle and forming deltaic equivalents to the estuarine Coal Measure cycles.

EXPLANATION OF PLATE I

Cores from the Rough Rock (Millstone Grit Series) near Eakring: the position of these cores is shown in Text-fig. 1.

(*a*) A typical sedimentary cycle from the lower part of the Rough Rock Series; the full extent of the top sandstone member has been omitted. This conforms to the ideal cycle illustrated in Text.-fig. 2.

(*b*) Slumped and contorted sandstone (grey) and shale, occurring at a depth of 2,170 feet, 30 feet below the top of the Rough Rock.



(a) (b)

ROUGH ROCK CORES FROM EAKRING.

The Granitization Process and its Limitations as Exemplified in Certain Parts of New South Wales

By Germaine A. Joplin

Abstract

In an attempt to dissect the granitization process in an area of regional metamorphism, it is suggested that granite is forcibly injected during strong compression, that the compressional wave passes upwards and outwards in advance of the magma, and that several changes take place before its arrival. Six stages in this process are recognized in the Cooma and Albury districts of N.S.W. : (1) Regional Metamorphism, (2) Superimposed Thermal Metamorphism, (3) Permeation without Magmatic Addition, (4) Addition from an Attenuated Magma, (5) Formation of a Potassic Wave-Front, and (6) Injection of the Magma as Concordant Intrusions. The conditions favouring granitization are discussed and the question of basic fronts is considered.

Introduction

READ (1948) has said very truly that " granitization means different things to different people ", and it is possible that much of the disagreement amongst petrologists over the matter of granitization is caused by the lack of a clear definition of the process ; thus, one geologist likens it to contamination, another to anatexis, and still another to metasomatism. Read definies it as " the process by which solid rocks are converted to rocks of granitic character without passing through a magmatic stage ". This may conceivably include all or any of the processes mentioned above.

Although much detailed work has been done on rocks believed to have suffered granitization, so far as I am aware little attempt has been made to study the phenomenon as a process and to trace its stages with a view to interpreting the physical conditions under which it operates. Processes such as hybridization and contamination have been studied exhaustively, and it is with some confidence that the petrologist can assume that a certain set of physical conditions obtained during the development of a certain hybridized or contaminated rock. It is true that xenoliths within a granite mass may be " converted to rocks of granitic character ", and have thus been granitized, but is this process similar to that which produces granitized rocks on a regional scale ? Unfortunately some authors, dealing with the origin of granites, have assumed this to be the case, and detailed work on xenoliths and other small-scale phenomena has been cited as evidence. With reference to this, Buddington (1948, p. 22) has warned—" the modification or replacement of metasediments has been demonstrated in many places with high degree of probability on a small scale, but the extrapolation of this principle as an accepted explanation of the origin of any large batholith is as yet wholly unwarranted."

In the present communication I propose to give a résumé of my observations in the Cooma and Albury districts of N.S.W., where there appears to be evidence of limited regional granitization. I will then outline the conditions that I believe to be necessary for the process to operate, and finally I will indicate what I consider to be the limitations of granitization and discuss the question of basic fronts.

Progressive Regional Metamorphism and Granitization at Cooma and Albury

The effects of metamorphism and the earliest stages of granitization are best studied in the Cooma district, but the more advanced stage of granitization, and the actual lacing of the schists with granites, are best seen in the Albury region which apparently represents a more deeply buried zone. The original lithological characters of the country rocks appear to have been almost identical in both areas.

At the time of the publication of the Cooma work, I considered that the granites were wholly magmatic, though much contaminated, and I recognized two types—a soda-rich and a potash-rich. Subsequent work at Albury, however, has led me to the conclusion that the potash-rich type is the product of granitization.

Studies in these two areas suggest that granite is forcibly injected during strong compression and that the compressional wave passed upwards and outwards in advance of the magma thereby causing the metamorphism of the country rocks before the arrival of the magma. Six stages in this process are recognized—

(1) Regional Metamorphism.
(2) Superimposed Thermal Metamorphism.
(3) Permeation without Addition from the Magma.
(4) Addition from an Attenuated Magma.
(5) Formation of a Potassic Wave Front.
(6) Injection of the Magma as Concordant Intrusions.

(1) *Regional Metamorphism.*—In the Cooma area (Joplin, 1942, 1943) I have shown that a series of interbedded pelites, psammo-pelites, and psammites had already been raised to the biotite-zone of regional metamorphism before the advent of the magma. The biotite-zone measures about $1\frac{3}{4}$ miles in width and has been traced for over 20 miles. On its western margin it passes out into a chlorite-zone which has been traced for 30 miles and has an average width of about $1\frac{1}{2}$ miles. On the north the series is cut off by younger granites and on the south overlain by basalts.

These two zones are also developed in the Albury district (Joplin, 1947), but are not so extensive, owing partly to the deeper burial of this region in the orogene, and partly to obliteration by later intrusions.

(2) *Superimposed Thermal Metamorphism.*—A rise in the thermal gradient is the first effect of the slowly uprising magma, and rocks that have already undergone metamorphism as the result of moderate compression now suffer a further change as the temperature rises, and stress temporarily wanes. Thus, at Cooma, before the magma actually is injected into the schists the high-temperature anti-stress minerals andalusite and cordierite are produced in its immediate vicinity. The andalusite-zone has a width of about ½ mile and has been mapped for a distance of about 20 miles.

This zone also occurs in the Albury district, where very coarse knotted schists are developed. In both areas these rocks occur as micaceous schists with porphyroblasts of andalusite and/or cordierite which usually contain carbonaceous inclusions. These occur in a fine lepidoblastic and granoblastic base of biotite, muscovite, andalusite, chlorite, and quartz.

(3) *Permeation without Addition.*—At Cooma the width of the outcrop of the permeation-zone is from 2 to 3 miles and it has been traced for about 17 miles. It might be mentioned here that all the zones at Cooma are developed on the western side of the granite and appear to have been only very slightly developed on the east. This may be due either to overthrust faulting or to a compression operating from the east and forcing the magma forward in a westerly direction.

When commencing work at Cooma, I considered that the permeation-zone was coincident with the boundary of a more psammitic sequence of country rocks, as the pelitic schists, which formed such conspicuous intercalations in the lower-grade zones, seemed to have suddenly disappeared. Soon, however, it became apparent that these rocks were represented in the permeation-zone by a granulite which was interbedded with the psammites and which was at first mistaken for concordant intrusions of granite. Near the boundary between the andalusite-zone and the permeation-zone the schists become less micaceous and more granular and felspathic, and an early development of spotting passes eastwards into a peculiar type of mottling (Mottled Gneiss—Browne, 1914).

These changes appear to have been brought about by a further rise of temperature in the vanguard of the magma, and under the deep-seated conditions of the permeation- or sillimanite-zone, porphyroblasts of orthoclase begin to develop in the andalusite-bearing schists and to isolate small rounded fragments of the schist, thus producing spotting. I have shown (Joplin, 1942, p. 180) with a series of equations that the orthoclase has apparently developed directly from the schist without addition of magmatic material. Thus, biotite breaks up to give orthoclase, quartz, and a new mica rich in the haughtonite molecule. A further amount of biotite develops filaments of sillimanite together

with quartz and more haughtonite, and potash is released. This released potash unites with andalusite to form a further quantity of orthoclase, or, if sufficient water be present as in the case of the Albury rocks, muscovite will arise with, or instead of, orthoclase.

Thus, orthoclase and muscovite form at the expense of andalusite and some of the biotite, and the rocks, though they still contain a little andalusite and sillimanite, are mineralogically not unlike granites in their composition. Nevertheless, there has been little or no addition from the magma, and practically no change in their chemical composition (see Tables 1 and 1*a*).

In discussing the origin of these paragneisses (Joplin, 1942, p. 182) I attempted to ascertain, by means of triangular diagrams, if there had been any magmatic addition, and concluded that a very small amount of albite may have been added, but that small differences in the amount of potash could be accounted for by slight variations in the original sediments. The changes, therefore, appear to have been brought about by heat and by heated magmatic waters and/or pore-fluids.

(4) *Addition from an Attenuated Magma.*—With a renewal of stress the more fluid components of the magma, and possibly a little of the complete magma itself, are injected into the schists. As the pelites have been prepared mineralogically for its reception, and the rocks are already at a high temperature, the process of granitization is facilitated.

Although little has been said of the psammo-pelites and psammites that are interbedded with the pelites, their pelitic matrix, or the narrow pelitic intercalations of the banded types, have undergone the same changes in the several zones, but on account of their higher quartz content and greater competence, they have maintained their characteristic field appearance throughout the permeation-zone and may still be recognized as psammites in this zone of granitization. Actually, the psammites are the most conspicuous rocks of this zone, and provide the sedimentary host for the most spectacular examples of *lit-par-lit* injection. As the interbedded pelites have already become coarse and felspathic, they afford little contrast with the igneous " lits " and are inconspicuous. Furthermore, discrete injection is to some extent inhibited in these pelitic rocks.

Lit-par-lit injection is well developed at Cooma where this stage of the granitization process was possibly accompanied by moderate compression. At Albury, however, discrete injection is not common and granitization appears to have been brought about by an infiltration of quartz-felspar magma. The psammites at Albury show an early development of oligoclase " phenocrysts ", and at a later stage oligoclase, quartz, aud orthoclase wedge their way into the fine granoblastic rock and envelop small xenoblasts of the same minerals. Mats of

minute sillimanite needles and small grains of cordierite may also be included in these enveloping grains.

The pelites now consist largely of quartz, orthoclase, and biotite, and these would be either in phasal equilibrium with the magma or slightly lower in its reaction series. In the first case, the minerals of the schist would form nuclei for the deposition of similar magmatic material, and in the second they might be partly resorbed by the magma (Nockolds, 1933). On the outer edge of granitization, where the quantity of magma would be small, it is probable that little resorption would take place, but nearer to the advancing magma the process would be more closely allied to contamination. The andalusite or sillimanite of the schist may remain as xenocrysts, as is commonly the case at Cooma, or they may react with magmatic fluids to form clots of mica, which is a common feature of the Albury rocks. Again, if sufficient magmatic material be present, they may go into solution to be precipitated later as pyrogenic minerals in a highly contaminated magma. Pink, pyrogenic andalusite contrasts with the colourless xenocrystal andalusite in the Cooma gneiss (Joplin, 1942, p. 177) and pyrogenic cordierite is found in a contaminated gneiss at Albury (Joplin, 1947, p. 108).

A distinction must be made between the granite-gneiss which is a granitized sediment, and the type that consists largely of magmatic material which has been either chemically or mechanically contaminated by sediment. Obviously there are all gradations between the two extremes, and the first is commonly threaded with veinlets of the second. As such veins become more abundant, and more magma arises to incorporate the sediment the amount of metasomatized schist becomes subordinate, and only contaminates the magma.

Granites of both types occur at Albury and at Cooma, but there is a slight proponderance of the granitized sediment or syntectic [1] granite. As the country rocks of both districts consist of interbedded psammites, psammo-pelites, and pelites, and as all types have probably contributed towards the formation of the granitized rocks, analyses of psammo-pelites were chosen for the calculation of theoretical syntectic granites, and it was found (Joplin, 1947, p. 117) that these closely

[1] According to Barth (1936, p. 840) syntexis means a melting together. He applies the term to rocks in which solid fragments have been assimilated by a magmatic liquid, as well as to rocks in which the liquid part has been less significant. He considers that it is essential only that, at one time, at least a portion of the rock was liquid.

I use the term in a more restricted sense, and refer to a syntectic granite when I mean one formed by the granitization of a sediment by a magma or its emanations, as opposed to one formed by the contamination of a magma by sediments. Thus, the second usage of Barth's term is adopted, since it is convenient to have the two names—syntectic granite when little liquid is involved, and contaminated granite when the liquid fraction is in greater prominence.

resembled actual analyses of granites believed to be the products of granitization.

The syntectic granite at both Cooma and Albury is commonly porphyritic, but it was found that the " phenocrysts ", which often exceed an inch in diameter, are composite units consisting of large grains of oligoclase and/or microcline that envelop xenoblasts of quartz and partly corroded grains of orthoclase. Thus, they are made up of both magmatic and xenocrystal minerals. Furthermore, the red-brown biotite of the schist is often associated with brown magmatic biotite. The xenocrystal potash felspar is always orthoclase, but material of magmatic origin is usually microcline or finely striated orthoclase, the lamellae possibly representing sub-microscopic intergrowths of soda-felspar. It is probable that much of the " magmatic " potash felspar has been dissolved out of the schist by the soda-rich magma and re-deposited. Xenocrystal orthoclase is often much altered to myrmekite, thus indicating the high soda content of the magma.

(5) *Formation of a Potassic Wave Front.*—In the foregoing it has been shown that the bulk of the potash felspar in the syntectic granite has been provided by the sedimentary rock, and that it is possible that the magma may have contributed only soda and silica. Although veins, stringers, and small dykes of potash-rich pegmatite invade both gneisses and schists, it seems evident that the soda-rich magma is the more important factor in granitization. Furthermore, though not confined exclusively to the outer margin, these pegmatites are concentrated at the outer limit of granitization, and I believe that this has some significance.

If stress continues to operate during the advance of the magma the orthoclase of the sediment, already incorporated in the syntectic granite, becomes albitized and myrmekitized, and the displaced potash is driven forward into regions of less pressure. Thus a frontal wave of potash-rich emanations proceeds in advance of the uprising magma, sodium silicates taking the place of potassium silicates in the region of strongest compression. This seems to suggest that elements with a large ionic radius are displaced by those with a smaller in the zones of maximum compression, but this is contrary to the belief of Lapadu-Hargues (1945), who maintains that the elements with the smaller ionic radii have the greatest mobility and travel furthest.

The potash-rich emanations could either form an outer zone of potash metasomatism or they could deposit potash-rich minerals in small openings in the less compressed zone in the form of veins and stringers. If a wave of compression is suddenly followed by a short period of tension—a not uncommon occurrence during a period of diastrophism—there might even by a surging back of the potash pegmatite to fill tensional cracks and dykes.

Barrow (1893) described fringes of muscovite-pegmatite on the southern margin of the older granites in the South-Eastern Highlands of Scotland, and this was subsequently interpreted (Harker, 1909) as the straining off of the liquid phase of a partly consolidated magma by filter-press action. Such a frontal wave carrying potassium silicates possibly represents the " ichor " of Sederholm (1907) and is responsible for migmatization, *lit-par-lit* injection and pegmatite veins.

In discussing the mode of formation of the gneisses of New Jersey, Fenner (1914) states—" the advance of the main body of magma would be preceded by that of a dilute portion, which would be able to impregnate the wall-rock with facility and initiate processes of transformation and solution which the more concentrated body following would carry further towards completion." It is sometimes assumed that pegmatites are the final stage after the separation of the granitic phase, but the phenomenon noted by Fenner is inexplicable on this assumption, since the later differentiate appears to arise in advance of the magma. Fenner rejects the possibility of the squeezing out of a partially differentiated magma and says with regard to the gneisses—" their origin must be looked for in a process involving the injection of a thinly fluid granitic magma between the layers of an original rock of laminated structure." It is possible that Fenner envisaged a process similar to that which I have described in connection with an attenuated soda-rich magma, but the potash content of the New Jersey igneous " lits " suggests that they may represent the stage here described. Barth (1936) considers that the movement of material within the orogenes is facilitated by the original pore-fluid of the country rocks, thus the advancing wave of potassium silicates, together with volatiles from the uprising magma, and the pore-fluid of the country rocks, could provide the " thinly fluid granitic magma " suggested by Fenner.

Billings (1937) has described potash metasomatism from New Hampshire, and points out that the rocks were already in the sillimanite-zone of regional metamorphism before they were metasomatized. He believes, however, that the potash solutions were derived directly from an igneous body.

Misch (1949a) also believes that granitization is preceded by fairly high-grade regional metamorphism, and considers that potassic solutions were the dominant agent. He describes potash-rich types in the outer zones, but it is significant that rocks of the inner zone contain considerable oligoclase.

In discussing the replacement origin of the Singo granite of Uganda, King (1947) mentions the fact that potash felspar is more abundant in the marginal phases, and is generally later than the plagioclase. He attributes these facts to the existence of two possible factors—the fixation of migrating K may have predominated during the later stage

of the evolution of the batholith, and/or the potash may have been capable of travelling a greater distance than the soda emanations. Although King does not suggest a wave-front of potash minerals, his observations are in harmony with such a concept.

(6) *Injection of the Magma as Concordant Intrusions.*—In the Albury district the formation of the syntectic granite appears to have been followed by a period of waning stress and the magma, only very slightly contaminated by sediments, has poured through as a series of small concordant intrusions. These sheets consist mainly of oligoclase-microcline-granites and aplites, though microcline-pegmatites are often associated with them and it is sometimes difficult to determine their relative ages. In general the pegmatites appear to be later. The oligoclase-granites sometimes contain a little xenocrystal andalusite and mica, and small red garnets, apparently pyrogenic, are present in some of the larger intrusions. Read (1931) has remarked upon the close association of garnet-bearing oligoclase granite and potash-pegmatite in the Loch Choire Complex of Sutherland, and considers that the oligoclase-rich rocks are slightly earlier.

At Cooma stress appears to have been renewed after the formation of the syntectic granite, and excess magma has been squeezed out as a marginal fringe into the region of less pressure. The Cooma region possibly represents a higher level in the orogene than that of Albury, since the granite intrusions are not abundant in the former area.

Conditions Necessary for Granitization

The present study seems to indicate that certain physical and chemical conditions must obtain before granitization can take place on a wide scale. In the first place, there must be a directed pressure so that fluids may pass from a zone of strong compression to one of less compression. Secondly, the temperature must be high so that the sedimentary rocks are in a high grade of metamorphism before they are subjected to the action of these fluids. Thirdly, the close proximity of a slowly advancing magma seems a necessary assumption. Finally, the composition of the sediments must be such, that when subjected to high-grade metamorphism, they will develop minerals that will be in phasal equilibrium with the advancing magma, and the composition of the magma must be such that granitization may take place without a great deal of magmatic addition. In general, normal pelitic sediments will recrystallize to give orthoclase felspar, biotite and quartz, and the magma would be required only to supply the necessary soda to convert them to rocks of granitic composition. In the case of abnormal sediments with a high soda content the last two conditions would not be necessary.

Unlike reciprocal reaction, which Nockolds (1931) has said " is the very basis of contamination ", I consider that regional granitization is

a one-way process. Materials pass outwards from a highly compressed zone and a two-way interchange is necessarily inhibited. When the magma is finally intruded, however, fragments of the granitized schist may be rifted off and suspended in the magma, and these may then undergo reciprocal reaction since directed pressure can no longer operate and a two-way interchange is possible.

The Limitations of Granitization

If the term granitization is used in its widest sense, that is as " any process which converts a rock to one of granitic character without passing through a liquid stage ", there would appear to be a number of processes capable of bringing this about and no limit to the development of granitized rocks.

Reference to the literature, however, will show that rocks converted into ones of granitic character by processes such as hybridization or contamination are of very limited extent. There are many instances of xenoliths being so converted, but it is usually found that the wall-rocks of the intrusions containing these xenoliths are but little affected by granitization and that their contacts are sharp and well-defined.

If it be assumed that different physical conditions obtain at different levels in a geosyncline, then it can be assumed that batholiths invading the deepest zone are subjected to the strongest compression. Under such conditions anatexis may take place in the lowest zone of flowage, and granitized rocks, similar to those that have been described from Fennoscandia and elsewhere, might be produced. At a slightly higher level, but still within a zone of strong compression, granitized rocks may be produced on a regional scale by a process of metasomatism as described above.

At higher levels in the orogene, magmas would not be subjected to so great a compression, no marked differences in potential between adjacent zones would exist, and conditions would not be suitable for regional granitization. At these levels, however, very limited areas of granitized rocks may be produced by reciprocal reaction, or in small areas of local compression, by a process such as that envisaged above.

At still higher levels, within the zone of fracture, a difference in potential may again exist and fairly widespread granitization may take place. In cupolas and such high-level intrusions, pressures may be set up as the result of the differentiation of highly fluid magmas, and if these pressures within the magma-chamber exceed those acting upon the retaining walls and roof, then magmatic material will pass outwards into the zone of less pressure and granitize the country rocks. In this case pressure will not be maintained for any length of time, and once relieved probably will not be renewed, so granitization at this level would not be on so large a scale as in the case of the very deeply buried

zones, and at this higher level much of the magma would be poured out into fissures to form dykes and veins. Furthermore, although the wall-rocks may have been subjected to high-grade thermal metamorphism, prior to granitization, this effect would not be comparable in extent to the sillimanite-zone of regional metamorphism.

It is possible that the granitized rocks of the Inyo Range (Anderson, 1937) and some of those of the South of England (Brammall and Harwood, 1932) may have developed at this level.

The Question of Basic Fronts

If the process of granitization is a one-way one, then there must be some displacement of original material in the direction of the lower pressure areas, but when the process takes place on a regional scale it is doubtful whether the elements are fixed to form a front.

There is no doubt that basic fronts are developed about xenoliths and very small intrusions (Joplin, 1935), but there is little information to indicate that they are developed on a large scale. Lapadu-Hargues (1945) has assembled a great many analyses in support of this conten-

Table I

	I.	*II.*	*III.*	*IV.*	*V.*	*VI.*	*VII.*
SiO_2	54·18	58·87	56·40	54·63	56·05	59·05	61·13
Al_2O_3	25·48	21·23	23·20	25·35	24·91	22·04*	23·43
Fe_2O_3	2·99	2·47	1·30	2·40	1·22	1·48	0·09
FeO	3·08	4·05	5·22	4·64	4·76	5·16	4·84
MgO	3·13	2·98	3·24	2·75	2·51	2·37	1·99
CaO	0·41	0·12	0·63	0·65	0·51	0·65	0·63
Na_2O	0·73	0·60	0·61	0·62	1·06	0·81	1·08
K_2O	5·70	5·73	5·65	6·28	6·12	5·85	5·84
H_2O+	2·88	2·59	2·77	1·25	1·23	1·17	0·26
H_2O-	0·48	0·22	0·30	0·26	0·22	0·18	0·20
TiO_2	0·73	0·84	0·57	0·86	0·86	0·68	0·72
P_2O_5	0·07	0·05	0·06	0·20	0·14	0·18	0·24
MnO	0·03	0·02	0·01	0·05	0·11	0·05	0·09
ZrO_2	nd.	0·02	0·05	0·15	0·09	0·19	0·16
C	0·34	0·16	0·51	—	—	—	—
	100·23	99·95	100·52	100·09	99·79	99·86	100·70
Sp. Gr.	2·80	2·78	2·85	2·83	2·85	2·82	2·81

I. Chlorite-sericite-phyllite (chlorite-zone) Cooma. Joplin, 1942. *Proc. Linn. Soc. N.S.W.*, lxvii, 181.
II. Mica-schist (biotite-zone). Ibid.
III. Knotted andalusite-schist (andalusite-zone). Ibid.
IV. Spotted granulite (boundary of andalusite and permeation-zone). Ibid.
V. Mottled gneiss (permeation-zone). Ibid.
VI. Mottled gneiss (permeation-zone). Ibid.
VII. Mottled gneiss (permeation-zone). Ibid.

* Al_2O_3 incorrectly stated as 22·95 when originally published.

tion but, although these analyses represent a number of different metamorphic grades, they also represent a great variety of rock-types, and generalizations based upon them are of little value. For such a study to be satisfactory one iso-chemical series, within a single area, should be studied in the several grades of metamorphism.

In an attempt to make such a study the analyses of seven pelites from Cooma in the four zones outside the zone of granitization are listed in Table I, but a direct comparison is unconvincing since the rocks vary in density and the analyses, therefore, represent unequal volumes of rock. They are recalculated in Table IA so that a comparison of equal volumes may be made. The least altered rock, of the chlorite-zone, has been chosen as the standard, and since the biotite-schist is 0·02 lower in density (i.e. 0·71 per cent lower) an equal volume of this rock should weigh 0·71 per cent less than that of the chlorite-schist. Similarly, the andalusite-schist should weigh 1·80 per cent higher. Although there are variations in the amount of magnesia, lime, and total iron, they indicate no fixation within any single zone and the differences can be accounted for in the slight variations which occur in the composition of the original sediments.

The syntectic granites at Cooma and at Albury are very rich in mica, and this may be true of all granites that have originated by a process of granitization. Actually, there may have been little displacement of material in these regions except, perhaps, the replacement of potash-felspar by soda-felspar, and the driving out of the potash. Eskola (1948) considers that the process of granitization is one of metasomatism, with subtraction as well as addition, but points out that the changes do not occur at constant volume. He considers that volume increases in the

TABLE IA

	I.	*II.*	*III.*	*IV.*	*V.*	*VI.*	*VII.*
SiO_2	54·05	58·46	57·13	55·18	57·17	59·52	60·90
Al_2O_3	25·41	21·09	23·49	25·60	25·41	22·22	23·35
Fe_2O_3	2·99	2·45	1·31	2·42	1·24	1·50	0·09
FeO	3·08	4·02	5·28	4·69	4·86	5·21	4·82
MgO	3·12	2·97	3·28	2·78	2·56	2·39	1·99
CaO	0·41	0·12	0·64	0·66	0·52	0·66	0·63
Na_2O	0·73	0·60	0·60	0·62	1·08	0·82	1·08
K_2O	5·69	5·69	5·74	6·34	6·25	5·90	5·82
H_2O	3·35	2·79	3·11	1·52	1·48	1·36	0·46
TiO_2	0·73	0·83	0·58	0·87	0·88	0·69	0·72
Etc.	0·44	0·25	0·64	0·40	0·35	0·43	0·49
	100·00	99·27	101·80	101·08	101·80	100·70	100·35
Total iron as Fe_2O_3	6·41	6·92	6·98	7·63	6·64	7·09	5·46

Analyses of Table IA recalculated as explained in text.

granitized zone are accounted for by doming. Misch (1949, a and b) also considers the process to be one of metasomatism, and believes that only alkalies, with varying small amounts of silica, are added. Unfortunately his work is not supported by chemical analysis, but his field observations do not support the idea of basic fronts.

Another attempt to examine the behaviour of a single iso-chemical series on the outskirts of a granitized area was made by recalculating the analyses of rocks in the six outer zones of the Stavanger region of Norway (Goldschmidt, 1920), so that equal volumes of these rocks might be compared (Tables II and IIA).

Reference to Table IIa will show that magnesia and lime are low in the two outer zones, which may mean that there has been some fixation of these oxides in the zones represented by analyses III, IV, V, and VI, and total iron may have been fixed in the zone represented by analysis II. The most striking feature of the table, however, is the marked increase of potash in the three outer zones, thus suggesting that the incoming soda has replaced potash which has passed outwards to the zones of less compression. This feature was not shown by the Cooma

TABLE II

	I.	*II.*	*III.*	*IV.*	*V.*	*VI.*
SiO_2 . .	58·32	57·29	60·62	62·40	64·35	64·70
Al_2O_3 .	20·00	20·60	18·50	16·27	16·54	15·45
Fe_2O_3 .	2·01	2·40	1·32	1·44	2·24	1·36
FeO . .	4·98	5·48	5·65	5·78	3·92	4·18
MgO .	1·85	1·76	2·42	2·19	2·04	1·48
CaO . .	0·66	0·37	1·66	2·07	2·04	2·92
Na_2O. .	1·26	1·40	1·81	2·28	2·00	3·09
K_2O . .	4·49	4·30	4·02	3·16	3·82	3·46
H_2O+ .	4·05	4·00	2·92	2·25	1·73	1·82
H_2O- .	0·05	0·05	0·17	0·16	0·12	0·15
TiO_2 .	0·98	0·97	0·80	0·81	0·70	0·59
P_2O_5 . .	0·15	0·14	0·08	0·16	0·17	0·19
MnO .	0·22	0·41	0·07	0·35	0·14	0·05
BaO . .	0·10	0·10	—	0·07	0·11	0·10
CO_2 . .	0·43	0·05	—	0·52	0·13	0·85
S . .	0·06	0·11	0·05	0·04	—	0·05
C . .	0·36	0·81	—	0·10	—	—
Cr_2O_3 .	0·02	—	—	—	—	—
V_2O_3 .	0·03	—	—	—	—	—
	100·02	100·24	100·09	100·05	100·05	100·44
Sp. Gr. .	2·798	2·862	2·838	2·814	2·812	2·777

I. Quartz-muscovite-chlorite-phyllite, Stavanger, Norway. V. M. Goldschmidt. *Videnskaps.-Akad. Mat.-Nat., Skrifter*, 1920, 110.
II. Quartz-muscovite-chlorite-garnet-phyllite. Ibid.
III. Quartz-muscovite-biotite-garnet-phyllite. Ibid.
IV. Quartz-muscovite-biotite-garnet-schist. Ibid.
V. Quartz-muscovite-biotite-garnet-mica-schist. Ibid.
VI. Albite porphyroblast schist. Ibid.

TABLE IIA

	I.	*II.*	*III.*	*IV.*	*V.*	*VI.*
SiO_2 . .	58·30	58·44	61·43	62·73	64·62	63·98
Al_2O_3 .	20·00	21·01	18·75	16·35	16·61	15·28
Fe_2O_3 .	2·01	2·45	1·34	1·45	2·26	1·34
FeO . .	4·98	5·59	5·73	5·81	3·94	4·13
MgO .	1·85	1·80	2·45	2·20	2·05	1·45
CaO . .	0·66	0·38	1·68	2·08	2·05	2·88
Na_2O. .	1·26	1·43	1·83	2·28	2·01	3·04
K_2O . .	4·49	4·39	4·08	3·18	3·84	3·41
H_2O . .	4·10	4·13	3·13	2·42	1·86	1·94
TiO_2 .	0·98	0·99	0·81	0·82	0·71	0·58
Etc. . .	1·37	1·67	0·20	1·25	0·55	1·22
	100·00	102·28	101·43	100·57	100·50	99·25
Total iron as Fe_2O_3 .	7·21	8·31	7·22	7·42	6·45	5·62

Analyses of Table IIA recalculated as explained in text.

analyses, because at Cooma the potash-rich rocks mainly take the form of discrete injections.

Examination of the two iso-chemical series at Cooma and at Stavanger bears little testimony to the existence of basic fronts, though there is some suggestion of fixation in certain of the Norwegian zones, and further work might bring this out more clearly. Nevertheless, the fixation of elements to form fronts over a large area would be less likely than in a restricted area, where the country rock is more likely to be homogeneous both in composition and in structure. In a wide regional tract a certain amount of heterogeneity might be expected, and the passage and fixation of material would depend upon a number of factors—structure, such as bedding, joint planes, and schistosity, the amount of pore-fluid originally present, porosity, and the composition of the country rocks themselves. Certain of these factors might facilitate the passage of fluids, whilst others might impede it. In exceptional cases all factors might favour the fixation of certain elements, and in these cases basic fronts would develop, but I venture to suggest that such would be exceptional and rare.

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A Note on Chromite-Marbles

By Sir Lewis Leigh Fermor

Abstract

Chromite-marbles from India and Finland are compared.

In a recent article in the *Mineralogical Magazine* (xxix, pp. 594–601) Mr. Oleg von Knorring has noticed a new occurrence of uvarovite from Luikonlahti in northern Karelia in Finland, 30 km. N.W. of the Outokumpu copper mine.

In discussing the source of the chromium the author refers to the occurrence at Outokumpu of dolomite containing chromite mentioned by Professor Pentti Eskola (*Compt. Rend. Soc. Geol. Finlande*, 1933, No. 7, p. 33).

As I have on two occasions made detailed studies in the field in India of important occurrences of chromite I cannot help having views on the origin of this mineral. These two studies were of the chromite deposits of Baluchistan in 1916, and of Singhbhum in 1918. The results of this work were summarized in the Director's Annual Reports for the years in question (*Rec. Geol. Surv. India*, xlviii, p. 12, 1917 ; and 1, pp. 10–12, 1919, respectively). The incidence of other duties prevented my publishing a detailed account of this work, but the results of the field studies must be accepted as reliable because in each case I had with me in camp a section cutter, so that every evening I could examine under the microscope thin sections of the rocks collected the previous day.

The summary of these two studies is that in both ore fields the chromite deposits were associated with serpentinized saxonites and dunites, the chromite preferring the saxonite ; and the evidence was that the chromite was of primary magmatic origin contemporaneous with the saxonite and dunite and prior to the serpentinization.

Great abundance of chert and its mode of occurrence indicated that in Singhbhum serpentinization was effected by siliceous solutions, amongst the products being chromite-bearing cherts. In one place later carbonate solutions had led to the replacement of chert by calcite with the preservation of the chromite and the production of chromite-marble. In summary I wrote :—

" Too great emphasis cannot be laid on the chemical stability of chromite in nature. Chromite-bearing magnesian rocks have been replaced by silica with formation of chrome-cherts ; in one place later carbonate solutions have attacked the cherts with replacement to a marble containing unaltered chromite grains, giving, in fact, a chromite-marble. Subsequent solutions have veined this rock with quartz."

Professor Eskola is puzzled by his occurrence of chromite in dolomite but, as he writes :—

" If it could be taken for granted that the dolomite has been formed by a metasomatic replacement of an ultrabasic rock, say serpentine rock, then we could easily understand the chromite crystals as relics from the primary phenocrysts once settled together with the olivine."

Such an explanation would be parallel to that adopted by me for the Singhbhum chromite-marble, and would pay due regard to the great stability of chromite in nature, and would render it unnecessary to regard the chromite in his dolomite as of hydrothermal origin. However, Professor Eskola prefers the latter explanation, for he concludes his paper with the words :—

" The chromite, as well as all the other chromium-bearing minerals of this locality, is in all probability of hydrothermal origin. The occurrence of chromium at Outokumpu illustrates the ability of this element to migrate and to take part in metasomatic replacements."

Of course, I am aware of the writings of Sampson, Ross, and others who regard a part of the world's chromite deposits as of hydrothermal origin. But in view of the extraordinary resistance of chromite in nature to all chemical attacks once it has been formed, I do counsel hesitation in ascribing the chromium contents of chrome-bearing silicates to derivation from chromite itself, unless the evidence is very clear, as it appears to be in some of the examples described by Mr. von Knorring. This, indeed, is to me one of the principal points of interest in this author's paper.

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Bristol, 6.

An Unusual Appinitic Sill Near Killin, Perthshire

By W. T. Harry

Abstract

An unusual appinitic sill intrudes and thermally alters regionally metamorphosed Dalradian sediments near Killin, Perthshire. The sill is composed of ultrabasic, basic, dioritic, and acid varieties, the last two being present only in minor quantity. The dioritic intrudes, and is chilled against the ultrabasic type. The appinitic varieties and contact Dalradian rocks are described together with their field relationships.

I. Field Occurrence

General.

THIS paper describes an appinitic sill intruding the Dalradian Series about three miles north of Killin, a village at the western end of Loch Tay, Perthshire. The intrusion is represented as an epidiorite upon the Geological Survey 1 in. sheet 46 (Scotland), hand-coloured, 1900 edition. The sketch-map below (Text-fig. 1) illustrates its geological setting.

The eastern portion of the sill is largely concealed, but good exposures

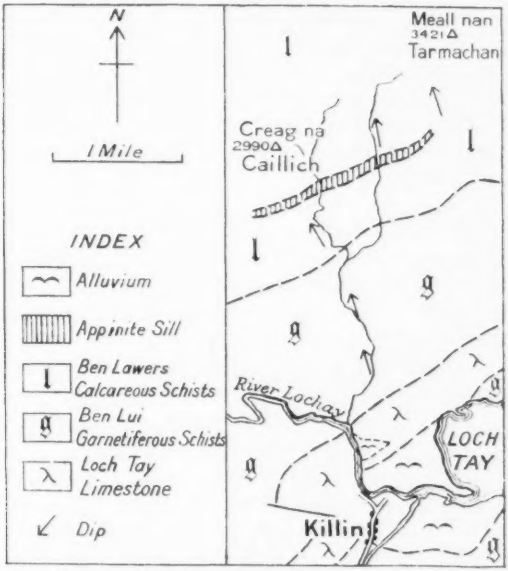

Fig. 1.—Geological map of the Killin district, Perthshire. Boundaries, excepting appinite, after Geol. Surv. 1 in., sheet 46 (Scotland), hand-coloured, 1900 ed.

occur between the western termination of the sill and the more easterly of the two streams shown crossing the sill on the sketch-map, Text-fig. 1. For convenience this stream will be referred to here as " the easterly stream ". In the beds of both streams good exposures occur, and excellent outcrops may be seen in the steep crags on the southern slopes of Creag na Caillich. The intrusion as a whole is massive, though well jointed, and weathers into dark-coloured rectangular blocks.

Contact relations with country rock.

The upper contact of the sill in the crags S.S.E. of the summit (2,990 ft.) of Creag na Caillich is referred to below as " locality I ". At this locality the sill is estimated to be about 150 ft. thick and presents a sharp contact against overlying bedded calcareous meta-sediments dipping roughly N.N.W. at a medium angle, which is the general dip direction of the schists on this, the south-eastern, limb of the Ben Lawers Syncline. As far as can be judged the contact between these rocks and the intrusion is inclined in much the same direction and so also is a set of joints in the sill. Good rectangular jointing along planes normal to the latter is also developed in the sill.

A few yards east of locality I, the sill transgresses the bedding of the calcareous meta-sediment and comes in contact with mica-schist overlying those rocks. Similar lustrous mica-schists dipping roughly N.N.W. at medium angles forms the floor of the sill, and its upper contact in the two streams shown on Text-fig. 1. Close to its lower contact in the easterly stream the intrusion is foliated parallel to the dip of the adjacent schists, but such directional structures have not been observed elsewhere.

Distribution and relationships of appinitic varieties within the sill.

Four appinitic varieties occur in the sill, ultrabasic, basic, dioritic, and acid. The last two are present only in small quantity.

Ultrabasic rock forms the upper parts of the intrusion and passes into a medium or fine-grained marginal chilled phase at the upper contact, as may be seen at locality I, in the easterly stream, and in exposures south of the summit of Creag na Caillich. At the last locality it overlies basic appinite, the contact between the two varieties being sharp. The same relation may be seen in a rock face below locality I and near the base of the hill. The contact surface here dips approximately north at an intermediate angle. Neither appinitic variety is chilled against the contact plane between them. In contrast with these sharp contacts the two types pass gradually into each other at a small waterfall in the easterly stream.

The dioritic variety forms a 4-ft. thick sheet, with chilled margins about 1 inch wide, intrusive into ultrabasic appinite below locality I.

The sheet dips roughly N.N.W. at about 45°. Dioritic appinite also forms fine-grained thin parallel-sided sheets of similar strike and dip in ultrabasic appinite near locality I.

Acid appinite occurs in a small outcrop near the base of the sill and about due south of the summit (2,990 ft.) of Creag na Caillich near a small bealach or pass.

II. Petrography

Ultrabasic appinite (*Text-fig.* 2*a*).

This weathers with a knobbly surface. In hand-specimen it is a dark green rock composed of highly sieved and irregular hornblende areas exhibiting "lustre-mottling". In thin-section pale-coloured large hornblende phenocrysts occur with moderate pleochroism, X = pale

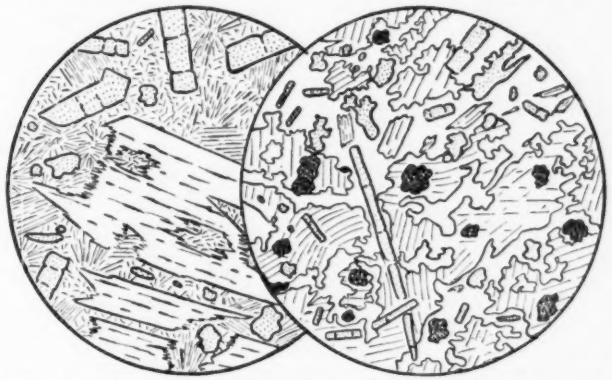

Fig. 2.—*A*. Ultrabasic Killin appinite. × 25 ordinary light. Green hornblende (centre) replaced by chlorite and tremolitic amphibole with epidote (stippled).
B. Dioritic Killin appinite. × 50 ordinary light. Green hornlende (ruled) epidote (stippled). Sphene (heavy stipple), albite-oligoclase (blank).

brownish-green, Z = green. These show very ragged outline and are highly sieved by, and cut by veinlets of, epidote, chlorite, and small colourless amphibole needles. The last three minerals form a groundmass constituting much of the rock and apparently developed in part, at least, at the expense of hornblende. The chlorite is pale green optically negative and may be well crystallized. Epidote, present in variable quantity, may become an abundant essential constituent, and may form grains or large broad idiomorphic laths. Albite-oligoclase sometimes forms a few small areas with refractive index about equal to that of Canada Balsam and only in accessory amount. Small muscovite plates may occur. Brown biotite, sphene, and carbonate areas are common accessory constituents.

Table I gives a chemical analysis of a specimen from a small waterfall in the most westerly of the two streams shown crossing the sill on Text-fig 1. The rock contains large hornblendes of an irregular frayed outline and abundant epidote in broad laths. The rest of the rock is essentially very pale green chlorite with an almost colourless amphibole in needles often arranged as stellate aggregates. Biotite and minute oligoclase areas are unimportant accessory constituents.

TABLE I

	I.	*A.*	*II.*
SiO_2	44·10	45·82	48·85
Al_2O_3	17·56	17·63	14·69
Fe_2O_3	0·71	2·01	1·56
FeO	6·82	6·20	5·33
MgO	14·46	13·53	16·28
CaO	10·08	10·94	8·33
Na_2O	1·02	1·34	1·32
K_2O	0·15	0·72	0·78
H_2O+	2·88	1·41	1·68
H_2O-	0·09	—	Nil
TiO_2	0·52	0·38	0·62
MnO	0·27	—	0·20
P_2O_5	0·03	0·08	0·03
CO_2	1·42	—	Nil
	100·11	100·06	99·67

NORMS

	I.	*A.*	*II.*
C.	0·71	—	—
or	1·11	4·45	5·00
ab	8·38	11·53	11·00
an	41·14	39·75	31·69
di	—	11·52	7·47
hy	22·58	3·59	25·36
ol	18·02	24·10	14·49
il	0·91	0·76	1·22
mt	0·93	3·02	2·32
cc	3·20	—	—

I. Ultrabasic appinite Killin. For location and description, see text. Analyst, Herdsman.

A. Olivine norite, Brocken, Hartz. Quoted by Washington, H. S. *U.S.G.S. Prof. Paper* 99, 1917, p. 652.

II. Basic appinite near ultrabasic limit, Killin. For location and description see text. Analyst, Herdsman.

Basic appinites.

In hand-specimens these may be distinguished from the ultrabasic appinite by their texture. Fresh fractures show abundant small well-formed dark green hornblende prisms a few mms. long and without preferred orientation set in a fine-grained pale greenish-grey or brownish coloured base. In thin-section the basic appinites show from almost

as little felspar as the ultrabasic type to about 15 per cent of felspar (by Shand Stage). Chlorite, generally speaking, is not so well developed as in the ultrabasic appinite, and may be absent in some specimens, especially those with most felspar. The green hornblende composing most of the rock is optically negative with $Z \wedge c$ about 20°, and pleochroism as in the ultrabasic appinite. It is, however, of better crystal form than the hornblende of the latter, much less sieved, more abundant as a rock constituent, and generally showing far less signs of replacement by chlorite, epidote, and colourless (or very pale green) amphibole. These three minerals may form a groundmass to the hornblende prisms. Epidote is present in variable amount. Clear albite-oligoclase, often untwinned forms highly poikilitic areas together with a little quartz and occasional potash felspar. Accessory constituents that may be present are brown biotite, muscovite, sphene, and opaque minerals. Some opalescent quartz may occur.

Table I gives an analysis of basic appinite from a locality about 300 yards E.N.E. of the exposure from which the analysed ultrabasic rock (see above) was collected. The specimen carries only small amounts of felspar and approaches the ultrabasic limit of the basic appinites. Hornblende is plentiful. There is less epidote and much less chlorite than in the analysed ultrabasic type. Colourless amphibole occurs in needles. Sphene is accessory.

Dioritic appinite (*Text-fig.* 2*b*).

This is medium-grained, with about 25 per cent of albite-oligoclase forming clear poikilitic areas set with small hornblende needles and epidote crystals. Green hornblende is abundant with subordinate epidote. Sphene, quartz, and biotite are accessory.

Acid appinite.

This is a coarse pegmatitic rock. Prismatic green hornblende crystals up to about 1 inch long and apparently without preferred orientation constitute roughly 30 per cent of the rock. The hornblende is strongly pleochroic, X = pale greenish brown, Z = deep green with a distinctly blue tint. Most of the rock is composed of quartz and albite-oligoclase often in micrographic intergrowth. Some epidote occurs and there are a few skeletal crystals of an ore mineral. Inclusions of epidote occur in the quartz.

Contact metamorphism.

Two specimens from about 40 ft. above the upper contact of the sill roughly S.S.W. of the summit of Creag na Caillich were taken to represent the normal regionally metamorphosed calcareous sediment. In thin section they show abundant small muscovite plates, epidote

granules, often concentrated in thin bands, chlorite, and a little brown biotite. A fine-grained base of clear albite-oligoclase may be present.

Where these rocks come in contact with the appinite they do not lose their general megascopic appearance, but they are toughened. Several such specimens were taken from the upper contact of the sill at locality I, and at a place S.S.W. of the summit of Creag na Caillich. In thin section they contain abundant microscopic needles of tremolitic amphibole, sometimes arranged in stellate aggregates, or perhaps concentrated in relatively coarsely crystalline small segregations, but usually forming a decussate felted ground-mass. Epidote, in grains or in thin laths, chlorite, and muscovite may occur. One well-banded specimen showed amphibole-rich bands which, compared with amphibole-poor bands in the same specimen, were impoverished in chlorite and epidote. The chlorite may form microporphyroblasts. Clear albite-oligoclase may occur, sometimes concentrated in thin bands, sometimes forming microveinlets crossing the banding of the hornfels. Sphene and biotite may be accessory. Irregular carbonate areas occur.

As representative of the normal mica-schist country rock two specimens were collected from 30 ft. above the upper contact of the appinite in the easterly stream. They are essentially quartz-biotite-muscovite-chlorite schists with some carbonate areas. The micaceous minerals demonstrate shearing and fracture-cleavage. Mica-schists were taken from the upper appinite contact about S.E. of the summit of Creag na Caillich and from a sheet in the appinite near to its lower contact in the easterly stream. In thin section they showed less indications of movement than the normal mica-schists just described. Directional textures were much less evident. Fibrous chlorite tended to segregate into small decussate patches. Epidote occurred as small granules.

III. Conclusions

The mineral assemblage and textures of the Killin sill are not those in normal igneous rocks ; of special significance is the presence of opalescent quartz and, in the coarse-grained acid variety, skeletal crystals of ore minerals. Crystallization of the sill cannot however be due to the regional metamorphism affecting the district, but must be of later date. This is indicated by the presence of chilled edges, the absence (with the exception of one small exposure) of any directional structures in the intrusion, and the formation of stellate amphibole aggregates by contact metamorphism of the country rocks by the sill. These original features would not have survived thorough recrystallization during the regional metamorphism that formed the surrounding mica-schists. The regionally metamorphosed basic intrusives of the

district (" epidiorites ") are schistose either marginally or throughout their mass.

In the ultrabasic appinite, replacement of hornblende by epidote and chlorite appears to have taken place within the cooling history of the body, since the ultrabasic appinite is intruded by a dioritic variety of appinite in which the hornblende shows little of such (deuteric) replacement. In the acid appinite epidote may be enclosed by quartz and must therefore be of earlier formation than the quartz. The felspathic varieties of appinite however show little evidence of the production of epidote from hornblende, although epidote seems to have crystallized, with acid plagioclase, after the formation of hornblende. As is well known, in the absence of stress co-precipitation of soda-rich plagioclase and epidote in stable equilibrium implies low temperatures, the same system crystallizing at high temperature to form basic plagioclase. The difference between the normative and modal composition of the appinite is therefore ascribed to persistence of crystallization at unusually low temperatures. This may have been due to the presence of abundant water. Hydrous minerals are common in the intrusion ; deuteric alteration is frequent. It may be remarked that the association epidote-soda-rich plagioclase in the appinite is essentially that of the helsinkites (albite-epidote rocks). The helsinkites have recently been discussed by Simonen (1948, pp. 50–53) who ascribes certain occurrences in Finland to late-magmatic water-rich solutions effecting the reaction basic plagioclase → albite + epidote. In the Killin appinite it is, from lack of evidence, uncertain whether epidote and acid plagioclase are low temperature primary magmatic minerals or whether they formed at the expense of earlier high temperature basic plagioclase as deuteric reaction products. In the first, as in the second case, abundant water probably influenced crystallization.

The Killin sill obviously may not be classified with the regionally metamorphosed epidiorites of the Perthshire Highlands. It may best be included in the " Appinite Suite " of MacGregor and Kennedy (1932, p. 107) a " diverse igneous assemblage " characterized by the presence of quartz and alkali felspar in rocks of all degrees of basicity and intruded after the regional metamorphism of the Scottish Highlands. In basic types the characteristic dark minerals are green hornblende and pale pyroxene. Reference may also be made to the original appinite description (Bailey, 1916, pp. 167–168) which comments that in appinites " Decomposition, probably in part juvenile, has often given rise to tremolitic hornblende, chlorite, albite, zoisite, epidote, and calcite ". The writer has examined slices of West Highland appinites in the collection of H.M. Geological Survey. These on the whole contain less epidote than the Killin rock and their amphiboles are usually dusty with inclusions whilst those of the Killin sill are not so.

The Killin sill is also thicker than the average Scottish appinite intrusion. The two analysed specimens of the Killin sill differ chemically from the appinites quoted by Deer (1950, p. 186) in, among other things, their higher MgO values and lower alkalies. They differ in the same way from the hybrids of Ach'uaine type cited by Read (1926, p. 163). Compared with basic and ultrabasic igneous rocks in general the Killin appinite is unusual (though not unique) because it combines a high MgO content with noteworthy quantities of alumina. This same feature is shown by an allivalite from Rum (Harker, 1908, p. 80) containing 17·56 per cent Al_2O_3 and 20·38 per cent MgO. The ultrabasic variety of Killin appinite shows chemical similarities with an olivine norite quoted in Table I. It is a matter for speculation whether the chemical peculiarities of the Killin sill may be connected with the activity of the water which is believed to have been present during crystallization.

ACKNOWLEDGMENTS

The writer is very grateful to Dr. J. E. Richey, F.R.S., for drawing attention to this occurrence, for critically reading the manuscript, and for making many helpful suggestions. Thanks also are due to Dr. A. G. MacGregor for permission to examine slices of West Highland appinites and for helpful discussion.

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The Paragenesis of the Varuträsk Pegmatite

By Percy Quensel

Abstract

A preliminary report is presented on the paragenesis of the Varuträsk pegmatite, situated about 10 km. from Skellefteå, in Sweden. Three main stages can be distinguished: (*a*) An epimagmatic-pegmatitoid stage during which the primary zonal development of the pegmatite body into border zone, wall zone, intermediate zones, and core was accomplished; (*b*) a hydrothermal replacement stage, divisible into a high temperature phase with a Li-replacement unit and a Cs-replacement unit, and a lower temperature phase with a cleavelandite replacement unit and a feebly developed fluorite unit; (*c*) a final stage of supergene alteration. The age of the pegmatite lies between 1650 and 1800 million years.

DURING the years 1937 to 1946 a series of thirty-seven papers under the common title "Minerals of the Varuträsk Pegmatite" was published by members of the staff of the Mineralogical Dept. of the University of Stockholm. In these papers some thirty minerals or mineral groups, characteristic of the pegmatite in question, have been described. A complete list of these minerals, including references, is annexed.

In many of the papers short indications were given of mineral associations in connection with the mineral then under consideration. Only in the papers by Adamson on the feldspar group and by Quensel and Gabrielsson on the tourmaline group, however, were some more detailed statements published on the distribution of these two mineral groups. A planned summary of the paragenetic development of the pegmatite was temporarily postponed on the chance that some further minerals might be forthcoming during continued work in the quarries. This was eventually found not to be the case. In the meantime other work intervened to delay my publication of the paragenetical problems with reference to the sequence of mineralization in the pegmatite.

The observations offered here are only to be considered as a preliminary report. It may be observed that the feature of special interest regarding this pegmatite is the exceptional enrichment of the rare alkalies: the high rubidium content in the abundant microcline-perthite and the vast quantities of the caesium mineral pollucite (with theoretically 42·53% Cs_2O).

History and General Outline

The Varuträsk pegmatite was discovered in 1933. The owner of the ground had noticed an outcrop of pure quartz in an outlying forest clearing and speculatively put in a charge for blasting. A fine-grained pink rock was thereby exposed. Dr. O. Baeckström, then chief geologist to the Boliden Mining Company, was shown a specimen and recognized

it as lepidolite. The occurrence of a lithium pegmatite on the grounds was thus confirmed. Further blasting was then undertaken by the Boliden Company, which resulted in the find of extensive occurrences of other lithium minerals such as spodumene, petalite, and amblygonite. As work continued during the following years, a great many other and rarer minerals came to light.

The Varuträsk pegmatite is situated about 25 km. S.E. of the Boliden gold mine and about 10 km. from Skellefteå town on the Baltic coast. The bus line between Boliden and Skellefteå passes within 1 km. of the quarries.

Through the courtesy of the Boliden Company I had the opportunity every summer in the course of many years to visit the deposits and to make collections of the minerals which had been brought to light during past mining operations. Work has successively been reduced during the last years and has for the present been suspended as the demand for lithium-ore has abated after the war.

The description of the minerals has been much facilitated by the permission granted by the Boliden Company for their qualified chemist, Miss Thelma Berggren, to analyse any specimens considered to require a chemical investigation. Miss Berggren's interested and efficient collaboration merits unreserved acknowledgment.

Dr. Erland Grip, now chief geologist of the Boliden Mining Company, kindly contributed much information while mining was still in progress, and has collaborated helpfully in the preparation of the annexed sketch-map, which in its general contour is founded on the prospecting charts of the Boliden Company.

The Varuträsk pegmatite forms a trough-like to tabular body, striking N.N.E.–S.S.W. In the eastern wing the dip is about 30° W.N.W., whereas the western wing lies all but horizontal. The exposed outcrops are about 200 m. in length. The thickness varies from some 3 m. to 30 m. (Text-fig. 1).

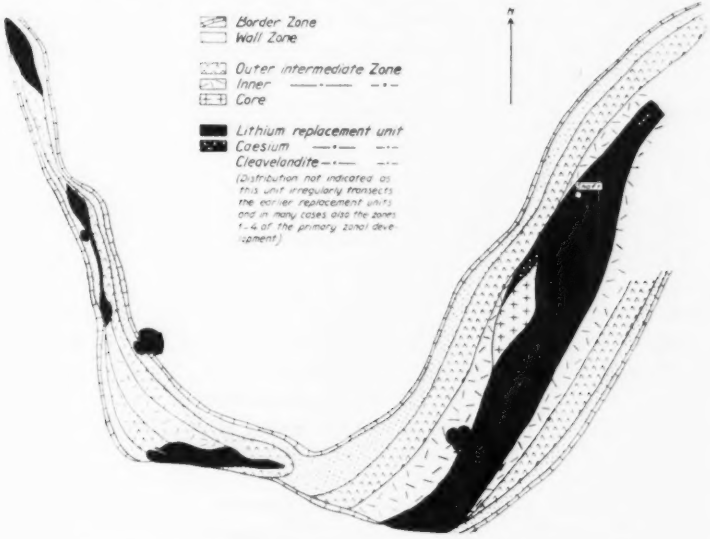
In this main distribution the pegmatite can be divided into two separate lenses, with only rocks of the wall zone in common. A pronounced zonal structure is in evidence. Superimposed on a primary zonal development, indicating the sequence of epimagmatic–pegmatitoid crystallization, different replacement units have invaded the pegmatite.[1]

Three stages in the mineralogical development of the Varuträsk pegmatite are clearly distinguishable. The first stage is taken to include the primary development of the pegmatite, representing the original

[1] In the following the terms "zones" and "units" of diverse character have been applied in the sense assigned by Shainin, Heinrich, and Cameron, Jahns, McNair, and Page. (V. E. Shainin, *Amer. Min.* xxxi, 1946, p. 329; E. Wm. Heinrich, *Amer. Min.* xxxiii, 1948, p. 420; E. N. Cameron, R. H. Jahns, A. H. McNair and L. R. Page, *Economic Geology*, Monograph No. 2, 1949.

zonal structure of the pegmatite body, formed by successive phases of crystallization from the walls inward. The second stage represents different units of replacement by hydrothermal solutions, which in many parts may to a great extent have obliterated the primary zonal partitions of the pegmatite. The third stage includes all phases of supergene alteration.

According to Fersmann's temperature scale of mineralization in pegmatites (Fersmann, 1931) the consolidation during the first stage should have taken place at temperatures over 500°. The mineral


Border Zone
Wall Zone
Outer intermediate Zone
Inner
Core
Lithium replacement unit
Caesium
Cleavelandite
(Distribution not indicated as this unit irregularly transects the earlier replacement units and in many cases also the zones 1–4 of the primary zonal development)
N

TEXT-FIG. 1.—Genetical development of the Varuträsk Pegmatite. Scale 1:1,600.

deposition of the second stage, caused by hydrothermal solutions at temperatures probably between 400° and 500°, represents the types "Natrium-Lithium-Pegmatite" and "Lithium-Natrium-Phosphat-Pegmatite" of Fersmann's phases F and G. Only some insignificant occurrences of fluorite indicate a continued mineralization below 400°. The supergene alterations of the third stage must naturally have taken place at essentially lower temperatures.

The pegmatite is surrounded on all sides by an amphibolitic rock of the same nature as that found in the surrounding rock formation. The pegmatite has not caused any marked change in the amphibolite along the contacts. In several places xenoliths of amphibolite are

found in the rocks of the wall zone. Definite reaction zones are then often visible. Along the contacts an inner zone of small red garnets may be seen, followed by a zone of albite and black tourmaline, the latter often in large individuals with a tendency to longitudinal orientation vertical to the contact. This indicates that epimagmatic temperatures must then have been prevalent.

The Primary Zonal Development of the Pegmatite (Stage I)

The primary structure of the pegmatite may be subdivided into several zones, each characterized by its own mineral composition. From the contacts inward they will be designated, according to recent American nomenclature, as the border zone, the wall zone, the intermediate zones and the core.

The Border Zone.—The border zone is of insignificant development but can be observed in most cases where the contact towards the amphibolite is exposed. It is generally only 1–3 cm. in thickness and consists of a fine-grained assemblage of quartz and muscovite. Adamson has a good reproduction of such a border zone from the upper contact of the western quarry in his paper on the feldspar group (Adamson, 1942, fig. 12).

The Wall Zone.—The border zone grades imperceptibly into the wall zone which is composed of a generally very coarse-grained quartz-muscovite rock with a varying quantity of black tourmaline. Occasionally some beryl is present. The muscovite is often developed in massive books up to 6 cm. in thickness and 20 cm. in diameter. The thickness of the wall zone may vary from 5 dm. to several m. In the part between the western and eastern expansions of the pegmatite, the pegmatite consists only of the wall zone where the quartz-muscovite assemblage in a very coarse-grained development attains a thickness of about 5 m. Near by, at a contact with amphibolite, large quantities of löllingite are found.

The Intermediate Zone.—The intermediate zone comprises the main part of the primary zonal pegmatite. There are indications that two phases can be distinguished, characterized by a somewhat different mineral assemblage. We may designate them as an outer and an inner intermediate zone. In the field, however, they are often so intermixed and overlapping that difficulties arise in keeping them apart. This is due to the circumstance that the somewhat later consolidated minerals of the inner zone have invaded and partly replaced the earlier consolidated minerals of the outer zone. The difference in mineral composition is presumed to be that the outer intermediate zone has a simpler mineral composition, mainly containing only microcline-perthite, quartz, and muscovite. In the inner intermediate zone an initial influx of lithium has taken place, resulting in the additional

appearance of the minerals spodumene and amblygonite. The muscovite in this zone may also acquire a certain amount of lithium, described by Miss Berggren as a muscovite with an appreciable amount of a lithium-muscovite radical (Berggren, 1939, p. 189).

The insignificant lithium content in a zone belonging to the primary zonal pegmatite would indicate that already at that period the pegmatite carried small amounts of lithium. This in its turn suggests that the later hydrothermal solutions with their high lithium content represent later derivations from the same granitic magma.

The intermediate zone, with its eventual sub-divisions, is taken to represent a definite stage in the sequence of consolidation of the primary pegmatite. The interval between the ultimate crystallization of the outer and inner zone has, however, probably been inconsiderable.

The individuals of microcline-perthite common to both the outer and inner intermediate zone can attain gigantic dimensions, probably as a result of a concentration of volatiles during the later stages of crystallization in the primary pegmatite. Adamson measured a microcline-perthite individual more than 3 m. in length, and even then it was only partially exposed. Amblygonite also occurs in huge individuals over half a metre in diameter in the inner intermediate zone of the eastern wing.

The Core.—Heinrich notes that the cores of the granite-pegmatites have a tendency towards simplification in mineral composition. Outer zones are said generally " to be composed of more than two essential constituents, cores are bi- or mono-mineralic. Regardless of the bulk composition, zones seem to become more siliceous towards the core ". The cores are therefore said to consist in most cases of massive white quartz (Heinrich, 1948, p. 440). This coincides well with the composition of the core as developed in the eastern wing of the pegmatite and there occupying a lens-formed central part, composed almost entirely of massive milky-white quartz. Though surrounded by mineral assemblages of the later replacement units, the core quartz does not show any obvious signs of replacement processes.

The Hydrothermal Replacement Phase (Stage II)

The second stage in the paragenetic development of the Varuträsk pegmatite includes all the secondary replacement units following the primary zonal consolidation of the pegmatite. The same difficulty as was met with in keeping apart the distribution of the two presumed intermediate zones of the first stage arises in an ever higher degree with regard to eventual different units of the second stage, as the hydrothermal solutions in their replacement activity often diffusely traverse the earlier zonal development of the pegmatite. They may follow pre-existing fractures or veins as channels for further replace-

ment, or they may produce uniform replacement masses of large zonal sections. In attempting to distinguish the sequence and distribution of different replacement units, the declining temperature during the active period of the hydrothermal solutions has been regarded as an essential controlling phenomenon. A bi-partition has therefore been tentatively made between a high temperature hydrothermal phase and an intermediate temperature phase. According to indications of the mineral sequence in the field, a further partition of each phase into several different units is suggested. The mineralization during the high temperature phase has often attained the form of extensive bulk replacement, whereas solutions of lower temperatures have in many cases been confined to fracture-controlled replacement.

High Temperature Hydrothermal Phase.—If with reference to the existing mineral assemblage the temperature interval, according to Fersmann's temperature scale, is taken to lie between 400° and 500°, the high temperature phase of hydrothermal replacement in the Varuträsk pegmatite would represent a mineralization near the 500° limit. Two replacement units of a high-temperature phase may probably be distinguished. During the period of the first unit the solutions have, with reference to their alkali content, mainly carried lithium. During a second and later unit, with a more restricted distribution, large quantities of caesium have been added.

The Lithium Replacement Unit.—The name lithium replacement unit is not meant to signify that the hydrothermal solutions of later units did not carry lithium. The name is only meant to indicate that the solutions of this unit were characterized by their very high lithium content and their relative scarcity of those alkalies which dominate in the solutions of the later units (caesium and sodium).

The minerals which may be taken as representative of this unit are petalite, spodumene, lepidolite, red and green tourmalines, amblygonite, and quartz. Of these minerals spodumene and amblygonite have been indicated as being present already in the inner intermediate zone. It is of interest to note that when the same mineral occurs in different zones or replacement units it generally differs in colour or size or mode of growth. The lepidolite belonging to this unit is of a characteristic mauve colour, contrasting with the more generally light to dark grey lepidolite of later assemblages.

Perhaps the most characteristic mineral of this unit is petalite. I would estimate that about 1,000 tons of this otherwise rare mineral have been mined in the northern offshoot of the western wing. The petalite occurs in large cleavage plates several dm. in diameter. It is in general sub-translucent, but not infrequently large cleavage plates are sub-transparent to nearly transparent. In the latter case the mineral is of an uncommon and beautiful appearance.

The mauve-coloured lepidolite of this high-temperature unit is found in accumulated masses of approximately a hundred tons in the central part of the western wing.

The Caesium Replacement Unit.—The great masses of pollucite in the eastern wing seem to deserve a distinguished position within the high-temperature replacement units. It seems hardly plausible that hydrothermal solutions in one part could have carried mainly lithium as the principal alkali component and close by deposited large quantities of caesium in the form of the mineral pollucite. A certain break in the continuity of the highly alkaline solutions is therefore probable. The localized distribution of the principal pollucite area as a marginal unit along the border of the zonal quartz core in the eastern wing likewise seems to be indicative of changed replacement channels. These have probably followed the contact between the inner intermediate zone and the quartz core, there largely replacing the minerals of the intermediate zones. Fragments of microcline-perthite have been observed in pollucite (Adamson, 1942, p. 20).

A partition of many of the minerals of the high-temperature replacement unit is often clearly manifested. Petalite is concentrated within the western wing whereas pollucite, as already noticed, is mostly found in localized parts of the eastern wing. Spodumene, on the other hand, has a wider distribution on account of its recurring in different phases of the pegmatite evolution.

Intermediate Temperature Hydrothermal Phase.—The mineralization during this phase has been very extensive. The main distribution is localized to the western wing throughout its entire extent, whereas the eastern wing of the pegmatite is in most parts poorer in replacements belonging to this epoch. The prevailing and most characteristic mineral of the assemblage is albite, in general developed as cleavelandite. The name cleavelandite unit has therefore been taken to denote the predominant mineral of this phase.

The Cleavelandite Replacement Unit.—The cleavelandite unit represents the first sodic influx of importance during the paragenetic evolution of the Varuträsk pegmatite. Wherever this replacement unit has been active, cleavelandite is the predominant mineral. In many cases it is developed as fans or sunbursts, 10 cm. or more in diameter. The albite in non-cleavelandite development is scarce. It is principally concentrated within the peripherical parts of the pegmatite, usually developing there as a sugar-grained albite rock at or near the contact with the amphibolite. Small crystals of a dark blue indicolite are often dispersed throughout such a rock. The texture indicates a rapid crystallization due to the cooling influence of the wall rock. The albite in its different phases of development is singularly pure in composition.

Three analyses by Adamson give only 0·00%, 0·03%, and 0·26% CaO (Adamson, 1942, p. 43).

The cleavelandite replacement unit carries a large quantity of minerals not previously represented. The principal and most characteristic constituents, besides cleavelandite, are a glassy, often dark quartz, grey lepidolite, blue tourmaline and the manganese apatites (Mn-apatite, Mn-voelckerite). To this unit belong, further, cassiterite, uraninite (rare), triphylite, lithiophylite, varulite, columbite, tantalite, stibiotantalite, stibiomicrolite (rare) and the alloy allemontite (rare).

In this connection it would lead us too far to enter into the relative sequence of the minerals of this unit. Cases can be found in which cleavelandite is seen to intersect one or more of the connected mineral assemblages whereas in another case the same minerals intersect or replace cleavelandite. Though the whole assemblage evidently belongs in all its principal parts to the same replacement unit, certain minerals may during its period of duration have been deposited at an early stage, then partly dissolved, and subsequently re-deposited in a somewhat different form. Numerous minor reversals in the general sequence of deposition are thus to be expected as a matter of course.

In consequence of the fact that the cleavelandite replacement is prevalent within the western wing, the Li-Mn-phosphates and the columbium-tantalum minerals are mostly found in that part of the pegmatite.

The Fluorite Unit.—Fluorite is of very rare occurrence in the Varuträsk pegmatite. It has only been found as yet in a few specimens. A fluorite unit has been included in this survey merely to provide evidence that some hydrothermal activity has continued at lower temperatures, subsequent to the cleavelandite unit, but so insignificantly represented that it can only signify a declining and concluding phase of replacement.

Phase of Decomposition (Stage III)

The third stage in the mineralization of the pegmatite represents all phases of supergene alterations. The minerals of this stage include the usual decomposition products of many minerals of all earlier phases. It may suffice to mention in this preliminary report only the most significant alteration products with the derivative component in brackets when this is known: montmorillonite (petalite), eucryptite (pollucite), kaolin minerals (spodumene and pollucite), ferri-sicklerite and heterosite (triphylite), alluaudite (varulite), mangan-hydroxy-apatite and, as superficial coatings, manganese oxides.

Attempts have been made to determine the approximate age of the Varuträsk pegmatite by means of the radio-active minerals. In 1939

an isolated specimen of uraninite was found in a cleavelandite vein replacement together with dark quartz in the western wing of the pegmatite. Later some more but very insignificant specimens were found in the same assemblage.

Professor Walter Wahl of Helsingfors kindly undertook a determination of the Pb-isotopes (Wahl, 1940 ; and later personal communication). Five mass spectra were measured with a Zeiss automatic microphotometer. The isotopic proportions were found to be :—

Pb 206 81·94%, Pb 207 15·26%, and Pb 208 2·80%

Provided that the material investigated has not been exposed to later selective processes, Wahl estimated the age of the pegmatite as $1{,}700 \times 10^6$ years.

In 1946 S. Eklund calculated the age of the pegmatite from measurements of the ratio Sr^{87}/Rb^{87}. Eklund had made a new determination on the half-life of Rb^{87} which gave a value of $5{\cdot}8 \times 10^{10}$ years (Eklund, 1946). Since then O. Haxel, F. G. Houtermans and M. Kemerich have by a different method redetermined the half-life of Rb^{87}, giving $6{\cdot}0 \times 10^{10}$ years. In the report of the committee on the measurement of geologic time for 1949–1950 it is said that " Although the individual measurements by Eklund and Haxel *et al.* carry a ± 10–15% latitude, agreement is good and one would hesitate to infer at this stage that the value of $5{\cdot}9 \times 10^{10}$ years is somewhat in error ".[1] Eklund has, using his value of the half-life of Rb^{87}, estimated the age of the Varuträsk pegmatite as $1{,}740 \times 10^6$ years with a relative error of 12%.

The difference between Wahl's and Eklund's age determinations lies within the limits of experimental error. The approximate age of the pegmatite, taking an adequate latitude into consideration, must be taken to lie between 1,650 and 1,800 million years.

In concluding this scheme of the paragenesis of the Varuträsk pegmatite, I wish to emphasize that it can only claim to be a preliminary report. The mineral assemblages of different zones and units will probably require adjustments, especially with respect to the recurrence of a mineral in different phases. Further work will be necessary before any definite conclusions in this respect can be relied on. Both from field observations and from a theoretical point of view, however, the partition into an earlier stage, representing the primary zonal development of an epimagmatic-pegmatitoid period, and a later stage of hydrothermal replacement units, seems to be conclusive.

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APPENDIX A

PARAGENETIC DEVELOPMENT OF THE VARUTRÄSK PEGMATITE

STAGE I.—*Epimagmatic-pegmatitoid phase. Primary zonal development.*

1. Border Zone.: Fine-grained quartz-muscovite assemblage.
2. Wall Zone : Coarse-grained quartz-muscovite assemblage with black tourmaline and sporadic löllingite.
3. Outer Intermediate Zone : Albite, microcline-perthite, quartz, beryl.
4. Inner Intermediate Zone : Microcline-perthite, quartz, muscovite, lithium-muscovite, spodumene, amblygonite.
5. Core Zone : Massive, white, milky quartz.

STAGE II.—*Hydrothermal phase. Replacement development.*

A. High temperature hydrothermal phase. Bulk replacement.
1. Li-replacement unit. Mauve lepidolite, spodumene, petalite, quartz, red and green tourmaline.
2. Cs-replacement unit. Pollucite, quartz.

B. Intermediate to low-temperature hydrothermal phase. Bulk, fracture-controlled and vein replacement.
1. Cleavelandite unit : Cleavelandite, grey lepidolite, quartz (glassy, often dark) blue tourmaline, manganese apatite, manganese voelcke, rite, triphylite, lithiophylite, varulite, triplite, allemontite, cassiterite, uraninite, columbite, tantalite, stibiomicrolite.
2. Fluorite unit : Fluorite (only vein replacement).

STAGE III.—*Supergene alteration phase. Final stage.*

Montmorillonite, kaolin minerals, cookeite, eucryptite, varulite, ferri-sicklerite, heterosite, alluaudite, purpurite, vivianite, manganhydroxyapatite, manganese oxides.

APPENDIX B

LIST OF DESCRIBED MINERALS FROM THE VARUTRÄSK PEGMATITE 1937–1946

PRIMARY MINERALS.	ALTERATION PRODUCTS
I. *Native elements*	
1. Allemontite	1*a*. Arsenostibite
II. *Oxides*	
2. Quartz	
3. Cassiterite	
4. Uraninite	4*a*. Gummite, Uranium-ochre
5. Stibiomicrolite	
6. Columbite	
7. Manganocolumbite	
8. Manganotantalite	
9. Stibiotantalite	
III. *Sulphides*	
10. Löllingite	

IV. *Phosphates*

11. Amblygonite	11*a*. Pinite
12. Manganapatite	
13. Manganvoelckerite	
14. Triphylite	14*a*. Ferri-sicklerite Heterosite
15. Lithiophylite	15*a*. Mangani-sicklerite Purpurite Varulite Alluaudite
16. Triplite	
17. Mangan-hydroxyapatite	
18. Vivianite	

V. *Silicates*

19. The feldspar group	
20. Petalite	20*a*. Montmorillonite
21. Spodumene	21*a*. Kaolin minerals
22. Pollucite	22*a*. Eucryptite
23. The mica group	
24. The tourmäline group	24*a*. Cookeite
25. Beryl	

References (for Appendix B)

(*G.F.F.* = Geologiska Föreningens i Stockholm Förhandlingar. *Arkiv för kemi*, etc. = Kungl. Svenska Vetenskapsakademien, Arkiv för kemi, mineralogi och geologi.)

1. Allemontite	Quensel, P.	*G.F.F.* 59, 1937, p. 135
	Ahlborg, K., and Westergren, A.	„ 59, 1937, p. 140
	Wretblad, P. E.	„ 63, 1941, p. 19
2. Quartz	Quensel, P.	„ 64, 1942, p. 283
3. Cassiterite	Quensel, P.	„ 63, 1941, p. 300
4. Uraninite	Quensel, P.	„ 62, 1940, p. 391
5. Stibiomicrolite	Quensel, P.	„ 67, 1945, p. 15
6. Columbite	Quensel, P., and Berggren, Thelma	„ 60, 1938, p. 221
7. Manganocolumbite	Quensel, P., and Berggren, Thelma	„ 60, 1938, p. 225
8. Manganotantalite	Quensel, P., and Berggren, Thelma	„ 60, 1938, p. 225
	Quensel, P.	„ 63, 1941, p. 176
9. Stibiotantalite	Ödman, O.	„ 63, 1941, p. 289
10. Löllingite	Ödman, O.	„ 64, 1942, p. 277
11. Amblygonite	Quensel, P.	„ 59, 1937, p. 455
	Tengnér, S.	„ 62, 1940, p. 332
12. Manganapatite	Quensel, P.	„ 59, 1937, p. 257
13. Manganvoelckerite	Quensel, P.	„ 59, 1937, p. 259
14. Triphylite	Quensel, P.	„ 59, 1937, p. 78
	Björling, C. O., and Westgren, A.	„ 60, 1938, p. 67
15. Lithiophylite	Quensel, P.	„ 62, 1940, p. 291
16. Triplite	Mason, B.	„ 63, 1941, p. 285
17. Manganhydroxyapatite	Mason, B.	„ 63, 1941, p. 279
18. Vivianite	Mason, B.	„ 63, 1941, p. 288
19. The feldspar group	Adamson, O.	„ 64, 1942, p. 19
20. Petalite	Quensel, P.	„ 59, 1937, p. 150

21. Spodumene	QUENSEL, P.	*G.F.F.* 60, 1938, p. 201
22. Pollucite	QUENSEL, P.	,, 60, 1938, p. 612
23. The mica group	BERGGREN, THELMA LUNDBLAD, BRITTA	,, 63, 1941, p. 262 ,, 64, 1942, p. 55
24. The tourmaline group	QUENSEL, P., and GABRIELSSON, O.	,, 61, 1938, p. 63
25. Beryl	QUENSEL, P.	,, 59, 1937, p. 269

1*a*. Arsenostibite (after allemontite)	QUENSEL, P.	*G.F.F.* 59, 1937, p. 145
4*a*. Gummite, uranium-ochre (after uraninite)	QUENSEL, P.	,, 62, 1940, p. 393
11*a*. Pinite (after amblygonite)	QUENSEL, P.	,, 59, 1937, p. 464
Poly-irvingite (after amblygonite)	QUENSEL, P.	,, 59, 1937, p. 467
14*a*. Ferri-sicklerite (after triphylite)	QUENSEL, P.	,, 59, 1937, p. 85
Heterosite (after triphylite)	QUENSEL, P.	,, 59, 1937, p. 86
15*a*. Mangani-sicklerite (after lithiophylite)	MASON, B.	,, 63, 1941, p. 139
Purpurite (after lithiophylite)	MASON, B.	,, 63, 1941, p. 145
Varulite (after lithiophylite)	ERIKSSON, T.	*Arkiv för kemi*, etc. Bd. 23*a*, No. 8, 1946, p. 13
Alluaudite (after varulite)	QUENSEL, P.	*G.F.F.* 62, 1940, p. 300
20*a*. Kaolin minerals (after spodumene)	QUENSEL, P.	,, 60, 1938, p. 205
	ALVFELDT, O.	,, 63, 1941, p. 49
21*a*. Montmorillonite (after petalite)	QUENSEL, P.	,, 59, 1937, p. 152
22*a*. Eucryptite (after pollucite)	QUENSEL, P.	,, 60, 1938, p. 630
24*a*. Cookeite (after rubellite)	QUENSEL, P.	,, 59, 1937, p. 262

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The Significance of the Hydrothermal Stage in the Formation of Igneous Rocks

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ABSTRACT

A group of eruptive rocks (weilburgites), widespread in the Lahn-region, is discussed in respect to its genesis. Their close relation to the keratophyres suggests a later mobilization of the keratophyric magma through the volatiles originating from the ascending diabasic magma (allopegmagenesis). In accordance with the character of the weilburgitic magma its ascent was accomplished by adaptation to the orogenic process (gradational ascent).

Conditions of this kind might influence the magmatic evolution in several respects. They are intimately related to geological conditions. To them are referred the favouring of allopegmagenetic or even allomagmagenic rocks in Palaeozoic time, the possible difference in age between the beginning of ascent and the emplacement, the lack of correspondence in composition of some rocks with the composition of the originating magma. Thus, the question arises as to how far correlations may exist generally between the mode of magmatic evolution in space and time, the composition of the rocks and the geological age.

PETROLOGISTS are familiar with the statement that " the pneumatolytic stage marks the end of the period of actual igneous rock formation " (Niggli, 1929). Now, some twenty years ago I encountered a series of rocks, extensively displayed in the Lahn region, as small magmatic bodies of lenticular (fish-like) form. Up to that time the terms " dense diabase " and " amygdaloid diabase " were used for these rocks. But their closer investigation has shown that the consolidation of the magma from which they formed took place to a large extent in the hydrothermal stage, i.e. that there are rocks for which the above restriction does not seem to exist. Consequently we may speak of " hydrothermalites ".

I will now try to demonstrate in a few words the essential observations on which this statement is based. The mineralogical composition of the investigated rocks is a very simple one. It includes only alkaline felspars and chlorite as essential constituents. On the average the felspars make up 60 per cent to 65 per cent, with chlorite 30 per cent to 35 per cent and some 5 per cent accessory minerals. It is striking that among these latter there is no apatite, in spite of a P_2O_5 content averaging 2·5 per cent. Iron in the form of magnetite or ilmenite as well as in the form of pyrite occurs sparingly. Titanite is more frequent but as a whole unequally distributed and in an unusual form of distribution. The felspars, commonly elongated in the [100] direction, thus chiefly of lath-shaped fabric in thin section, are without exception

[1] Paper presented before Section C at the Edinburgh Meeting of the British Association, 1951.

nearly pure alkaline felspars. The An content does not exceed 5 per cent. Phenocrysts are mostly lacking, occurring sparsely in some occurrences, abundantly in a very few. The most characteristic feature is their variability of composition, including albite, orthoclase, soda-orthoclase, and anorthoclase. Albite predominates in some cases, orthoclase in others, both of them combined with varying amounts of soda-orthoclase. Occasionally this variability occurs within one and the same body. Then the potash generally seems to be concentrated in the outer parts of the mass. As to the *chlorite* one might at first be inclined to take it as a secondary mineral, resulting from the alteration of pyroxenes or olivine, and thus to suggest a spilitic character for the rocks. At first I also did so. Yet I did not think that the original rock was a diabase, but a keratophyre. Therefore, in my first publication, the term "Keratophyrspilit" (keratophyric spilite) was used. On further investigation, however, I had reason to reject the autometasomatic interpretation. But before we enter into a discussion of this question let us cast a look at the chemical composition of the weilburgites. The first significant property is the variability of the alkalies : the limit for K_2O being 0·5 per cent and 10 per cent, for Na_2O 0·5 per cent and 7·5 per cent, whereas the total ranges between 6·5 per cent and 11 per cent and the average is about 7·5 per cent. In the extreme members K_2O decreases with increasing Na_2O and conversely. Thus we may distinguish three groups in the weilburgitic series : the potassic group, the alkali-intermediate group, and the sodic group. MgO ranges between 1·5 per cent and 7·5 per cent, the total FeO (i.e. including Fe_2O_3) between 5·5 per cent and 13 per cent. For MgO + FeO the limits are 12 per cent and 20 per cent, but in 75 per cent of the rocks the amount exceeds 15 per cent. SiO_2 shows a narrow range between 42 per cent and 50 per cent. In the normative composition its quantity, in general, is not sufficient for saturation. If, as I believe, the chlorite is a primary mineral, the relatively high content of H_2O + cannot be an effect of weathering. In fact, practically all the analysed rocks were remarkably fresh. The H_2O content is nearly constant and is usually about 4 per cent. CaO shows the greatest variation and this variation occurs not only at different localities but often also within short distances in one and the same mass. Apart from the feeble anorthite content of the felspar, calcium carbonate, and titanite, there are normally no Ca-containing constituents. In rocks free from carbonate the content of CaO does not exceed 4 per cent, often it is less. And the same result is obtained for *all* the rocks when calcium carbonate is subtracted. There are other direct observations pointing to the allogeneous nature of the major part of the carbonate in the weilburgites:—

(1) relics of limestone not recrystallized, in the form of great blocks as well as minute fragments ;

(2) tongue-shaped apophyses of the surrounding magmatic material in the blocks and fragments of the sedimentary rock ;

(3) gradual dissolution of the limestone-boundary in the adjoining magmatic substance ;

(4) scattering of the inclusions to form isolated complexes of " amygdales ", the complexes quite irregularly bounded. In pillows concentric zones of amygdales around a limestone centre, their distance increasing towards the pillow border ;

(5) inclusions of dihexahedral quartz and of slate-fragments in the pesudo-amygdales ;

(6) reaction-rims around carbonate inclusions of different form ;

(7) corroded relics of fossils.

If we encounter these symptoms in numerous separate occurrences of the same series of rocks, then in my opinion, justification exists for assuming the allogeneous nature of the carbonate for the series as a whole. Then we are also justified in eliminating the carbonate for comparative and derivative, i.e. for genetic, investigations in general. In doing so the scattering in the composition disappears while, if it is not done, the natural uniformity of the weilburgites is hidden and the rocks are distributed over the trachytic, the andesitic, and the basaltic fields (Niggli, 1944).

Another important point concerns the sequence of crystallization of felspar and chlorite. In assuming the autometasomatic hypothesis and thus regarding the weilburgites as rocks of originally basaltic composition, two facts must be clarified :—

(1) The existence of the three groups, especially the divergence in the sodic and the potassic extremes. That is very difficult because of the abundance of potash-soda-felspars and the frequency of albitic zones surrounding these and of orthoclase zones surrounding the anorthoclase, as well as because of the absence of secondary calcic minerals in the carbonate-free members and the extremely high quantities of carbonate in other ones.

(2) The late crystallization of the chlorite with respect to the felspars. The chemical composition of the rocks is characterized by deficiency of SiO_2, high alkalies and abundance of $FeO + MgO$. Thus a normal crystallization should begin with olivine, perhaps in association with plagioclase, and end with augite and alkali felspar. Consequently it would be expected that the forms of the chloritic aggregates would to a certain degree be pseudomorphous after olivine. But no such pseudomorphs are encountered. The emplacement of chlorite is determined only by the felspar-crystals. I therefore conclude that the chlorite represents a primary crystallization product and that we have to do with an inverted sequence of the felsic and the mafic minerals.

However, as far as the chlorite is concerned, this indirect argument

may not be entirely satisfactory. But recently I encountered typical weilburgites in the northern Sauerland with only a minute quantity of chlorite and with a highly vitreous groundmass. Necessarily their content of 15·5 per cent FeO (total) + MgO must be contained in the glassy part and there must have existed a late liquid approaching chloritic composition. The above conclusion about the chlorites in the Lahn-rocks is confirmed by this observation in the weilburgite of Sauerland. Evidently such an inversion in the freezing process cannot be the result of a simple fractional crystallization. That was corroborated by trying by calculation to reach the weilburgitic composition from different basaltic compositions, whereas the same attempt for the keratophyre gave good results (Lehmann, 1950). Moreover we may refer to the absence of glassy rocks rich in the albite molecule, discussed by N. L. Bowen (1928). The results of calculations based on presumed assimilation of country-rocks followed by crystal fractionation were equally unsatisfactory.

But what mode of genesis may be assumed? One can hardly deny a close relation between the weilburgites and the keratophyres with respect to richness in alkali, a tendency to variation in the character of the alkalies, the kinds of felspars present and the deficiency of ore minerals. Further, the keratophyres are the oldest igneous rocks of the regions referred to. They are developed in the Middle Devonian. The weilburgites are encountered up to late Upper Devonian. They are succeeded by diabase in Carboniferous time. On this basis I assume that the contents of the deep-seated keratophyric magma-basin have undergone a later mobilization through the activity of volatiles, originating from the ascending diabasic magma. After the eruption of keratophyric magma the available energy in the remaining material was exhausted, the magma was cooling and at least the greater part of the felspars was already crystallized. The volatiles brought not only a supply of energy but also carried Fe and Mg in solution. Some exchange of substance took place. Fe and Mg were given to the magma, whereas SiO_2 was carried off and deposited at a higher level under different conditions. The widespread silification of rocks and ores in the Lahn region is probably the result of this process. From the point of view of the keratophyre the process may be called palingenetic, but in a specific sense, being limited to magmatic participants and to the volatile phase of one of them. I propose therefore the term *allopegmagenesis* for it, and the term *allomagmagenesis* for the further step, including the migration of the ascending magma itself into an intercrustal magmatic reservoir, the contents of which may just have crystallized or still be partly liquid. Some support for such a migration of diabasic material may be given in the presence of chromite in a few weilburgites, certainly a constituent not of keratophyric but of diabasic

provenance. It would be very hard to answer the question whether some of the alkali-diabases in the area are not allomagmagenic.

Although the autometasomatic character of the rocks must be rejected, nevertheless the mineral association requires a low temperature range during the period of ascent and consolidation. Only such constituents as anorthoclase (it is often corroded) and some potassium-sodium-felspar are to be attributed to the orthomagmatic state, originally existing in the keratophyric reservoir. For the weilburgitic period one may assume 500° C. as the upper limit of temperature, based on the absence of wollastonite in the reaction rims with limestone. Only for the rocks in the northern and southern border-zones of the Lahn basin the temperature may have been somewhat higher, say, 600° C. Titaniferous augite, as a reaction mineral, is restricted to these zones, and the same applies to the chromite.

There are other features, of a more general geological nature, which mark the specific character of the weilburgitic melt :—

(1) As already mentioned the magmatic bodies have overwhelmingly the form of flat cupolas or lenses, sometimes only of few decametres in length. On the other hand their number can be unusually great in a relatively small area, much greater than represented in the geological maps. Their long axes follow very closely the general N.E. trend of the country-rocks.

(2) This distribution continues even on a minute scale, and many of the so-called " schalstones " consist of keratophyric tuffs or sedimentary rocks infiltrated with weilburgitic material on a microscopic scale.

(3) A very conspicuous feature is the extreme rarity of something like feeding channels, i.e. dikes, vents, etc.

(4) Another astonishing fact may be mentioned : the apparent lack of weilburgitic tuffs, whereas a keratophyric tuffaceous phase of great importance is represented by unbedded and well-bedded material. In view of the high water content this behaviour of the weilburgitic magma is abnormal and it is to be supposed that unusual conditions must have existed, both as to the state of the magma and the mode of its ascent. The distribution and the geological appearance of the magmatic material require a behaviour inconsistent with a normal magma in the temperature-range in question. A normal magma would be of great viscosity. The actual geologic appearance suggests a magma of extremely high mobility.

General Conclusions

We will start the general discussion with the allopegmagenic process. The concept of fronts, magmatic and migmatic, is familiar to all petrologists. Such a magmatic front, I think, would be above all a front of liberated volatiles, and their setting free is effected by release of

pressure. The process is thus initiated by crustal movement or, maybe also, by the removal of magma from deeper seated to higher crustal zones. In my opinion our conceptions on the mechanism of magma-ascent are too much determined by the development of volcanic activity at present and in Neozoic time, where the pouring out of lava or magma is connected with visible vents and conduits or with lines of fracturing. Here the ascent may be and probably is effected in a direct way, as a single and continuous process (" legato injection " of R. A. Daly). The material produced is, in general, of basaltic composition. But is the same mode of ascent unreservedly to be assumed when connected with folding? Consider an example recently treated (Lehmann, 1951). It concerns an alkali-diabase from near Bissenberg in the Lahn-region. In this rock different stages of evolution have left their traces. We see crystals of enstatite, mainly altered to serpentine. Then follows the crystallization of β-leucite, nepheline, and analcite. Next came the crystallization of augite, and, finally, prehnite. That is not a straight line of evolution, but a very discontinuous course and it reveals the history of a long and complex development. Unfortunately, the history of rocks cannot always be deciphered as here. But this example warrants belief that the ascent of magma in folded regions often resembles a squeezing through rather than a bursting out, or the advance is by steps and not direct.

The effects of magmatic activity, accessible to observation, concern only the end-phase of the ascent. Thus we can range in their geological age only these effects. But we are unable in general to recognize the beginning of the ascent. In the Bissenberg diabase the manifestation of a change from sub-alkaline to alkaline tendency and, moreover, the serpentinization of the enstatite, in addition to later formation of augite in large crystals, suffice for the conclusion that there existed some widely spaced stages of evolution. Consequently it is to be supposed that, in some instances, the upward movement at times was interrupted and that the departure falls in another cycle of magmatic activity than the arrival in the position we meet now. Such a concept likewise is valid for the weilburgites, notwithstanding that there the change of composition was less a matter of the ascent than of the evolution as a whole. But I think that " gradational ascent " and, consequently, interrupted crystallization may be responsible for many irregularities in composition of rocks. Should not such discontinuity be the rule for intercrustal magmatic activity closely connected with folding or, more generally, with crustal movement? In the case of weilburgites there are visible arguments for the correlation with tectonics during the ascent and emplacement of the magma. I may refer to the extreme rarity of conduits, to the prevailing form of the magmatic bodies, to the megascopic and microscopic joining of magmatic elements with the

surrounding rocks and to the boudinage-like limbed dikes from the Königszug-mine in the Dill-region, described and reproduced by me in 1931 (Lehmann, 1931, plate 18, fig. 2). Furthermore, the two examples referred to support the conclusion that intercrustal magmatic activity was not always effectively restricted to the transfer of well-defined liquid material of constant composition from one place to another. This transfer included segregations from the liquid and reaction with slightly earlier magmatic material and surrounding non-magmatic rocks. The susceptibility of material at depth is much greater than in the moving crustal parts. What we can observe as a period of crustal movement probably corresponded at depth with much more intensive manifestations.

Now, as to the allopegmagenic process, the volatiles, escaping from the approaching diabase magma, gave up their thermal and chemical energy to the keratophyric mass. Whereas they themselves suffered a calorific loss, the keratophyre was thus enabled to dissolve a quantity of gas according to the existent pressure. The elimination of its vanguard of volatiles may have retarded the moving up of the diabase-magma. The ascent of the weilburgitic magma set in when its saturation with gas was completed and a certain excess of internal pressure was reached. In such a state and on account of its mobility, the magma became very susceptible to changes in the pressure of the overlying masses. But the internal pressure never was elevated to explosive force. The outer conditions were such that the superpressure in the system was held at a low degree. There existed, so to speak, a continuous adaptation to the relief of pressure, as the overlying schists moved upward. In correlation with the low temperature, the remaining energy of the weilburgitic magma was rapidly exhausted on its arrival in porous strata, such as tuffs. The liquid phase diminished through crystallization of chlorite or through consolidation as glass. An abundant vapour-phase arose, accelerating the loosening and breaking off of blocks of compact rocks such as limestone and, as the case may be, initiating chemical and metasomatic reactions. The significance of the nature of the invaded rocks is therefore evident, and is no less responsible for the unusual composition of the weilburgites than the primary magmatic material, the latter with regard to the alkalies, the former with regard to the calcium. The variability of calcium-content finally resulted. To be sure, one may select some of the thirty analyses containing calcium, as carbonate or as pyroxenic reaction-products, which have that element in amounts suitable for a basaltic composition. But what is to be done with the others which have no carbonate and accordingly a deficiency of calcium or with those containing 50 per cent calcium carbonate, an amount of calcium incompatible with basalts?

In the Vogelsberg and in the Westerwald basalts are the predominant

igneous rocks and certainly many of them have undergone intracrustal consolidation. A spacious formation of tuffs is present also. Nevertheless, rocks comparable with weilburgites are lacking. Evidently there was a different magma and a different evolution of magma. I think this may also hold good in other regions with a similar geological structure and the same geological position.

To what degree may allopegmagenic effects have been realized and to what degree may hydrothermalites be developed in the earth's crust during geological time? There are good reasons for assuming an augmentation of magmatic action the farther we go back in geological times. The sequence of magmatic events was more rapid. Also magmatic bodies in the crust are to be expected more frequently and closer together. Consequently, the conditions for allopegmagenesis and for allomagmagenesis were favoured. One would even hardly understand it if existing intrusive bodies were not influenced by later ascending magmas. Transport and exchange of substance thus may have been of great importance in Palaeozoic and Pre-Palaeozoic magmatic periods. Especially among the intrusive rocks allopegmagenic compositions are to be expected. Whether the allopegmagenic rocks are simultaneously hydrothermalites is another question. These may, as in the case of weilburgites, contain chlorite as a primary constituent. Weilburgites may represent, so to speak, a somewhat extreme product. It depends on the PTX conditions whether the chlorite can be replaced by biotite or even by amphibole. It does not seem beyond the range of possibility that, by means of allopegmagenesis, transition rocks could originate which would show a close resemblance to orthomagmatic mineral associations.

Hydrothermal rocks may in general, or even always, be derived rocks of magmatic origin and the results obtained from a study of the weilburgites warrant belief that allopegmagenesis did offer a favourable starting point for their origin. They are not products of residual solutions in fractional crystallization and the quotation of Niggli cited at the beginning of this paper is quite authentic when limited to pure magmatic descent. But the evolution of such rocks as weilburgites depends largely on suppositions not inherent in the principles and doctrines of magmas. Consequently, one cannot disprove interpretation of the genesis of weilburgites given here by means of these principles. Intracrustal movement is no less decisive for this genesis than the purely magmatic evolution. During periods of great magmatic activity the deep crustal parts can be assumed to have been extremely sensitive to any dislocating process. This increases the probability that different magmas, or separated magmatic bodies, interacted. And thus a dependence on geological age seems obvious. We should not, I think, evade the question put by Marcel Roubault : " Est-il bien certain,

après tout, que toutes choses se soient toujours passées autrefois comme de nos jours ? " (Roubault, 1949).

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CORRESPONDENCE

THE NAME " THOLEIITE "

SIR,—The widening use of " tholeiite " in areal geology, geochemistry, and geophysics prompts me to inquire whether the name will prove entirely satisfactory as a tool for earth science. Two reasons for doubt will be offered after a brief sketch of the history of the word has been presented.

It was introduced into German petrography by Steininger (*Geogn. Beschr. des Landes zwischen d. unteren Saar und d. Rheine*, Trier) in 1840. The authors of the classic Mull Memoir of the Geological Survey of Scotland (1924) selected the old word to designate one of the two magma-types found in the Thulean province of plateau basalts. In 1931 (*Summ. Rept. of Progress, Geol. Surv. of Gt. Britain*, p. 62), and with greater detail in 1933, W. Q. Kennedy (*Amer. Jour. Science* (5), xxv, 256) published the hypothesis that the tholeiitic magma has been so differentiated that it can be described as the parent of the world's andesite and the grandparent of the world's rhyolite. In contrast he found another primary magma, of the " olivine-basalt type ", to be the parent of trachyandesite, and grandparent of trachyte, and the great-grandparent of phonolite and other " alkaline " rocks. Three years later Kennedy, in collaboration with E. M. Anderson (*Bull. Volcanique, Internat. Union of Geodesy and Geophysics*, Sept. 22, 1936) postulated for the present geological epoch a thick, crystallized, tholeiitic earth-shell underlying the Sial of the continents and confined to these sectors, and resting on a world-circling, crystallized shell of olivine basalt. In 1949 W. Wahl (*Amer. Jour. Science*, ccxlvii, 156–160) expressed sympathy with that view of the outer basic shells of our planet as now constituted. In 1950 C. E. Tilley added still further to the dignity of " tholeiite " when in his Presidential Address to the Geological Society of London (*Quart. Journ. Geol. Soc.*, cvi, 37–61) he argued that tholeiitic magma has been the " primary " source of basic eruptives in deep-sea areas as well as continental areas.

My first objection to giving " tholeiite " such high distinction in earth science has to do with its spelling—a difficulty long felt by the conscientious teacher of petrography who wants his students to go to the roots of things. " Tholeiite " seems to have been derived from the name of a town of the Saar-Rhine district, mapped as " Tholey " in Stieler's great Handatlas

(1921 and earlier editions). Although Rosenbusch and Zirkel adhered to Steininger's spelling, K. A. Lossen (*Zeit. Deutch. Geol. Ges.*, 1898, p. 258) did not, preferring " tholeyite "—likewise the choice of M. Schuster (*Geog. Jahresheft*, xxvi, 1914, p. 242) and of G. Fischer as late as 1951 (*Geol. Rundschau*, xxxix, 59). J. W. Judd (*Quart. Jour. Geol. Soc.*, xlvi, 1890, p. 379) chose " tholeite ", as did the editor of the *Summary Rep. of Progr., Geol. Surv. of Great Britain* (1912 and 1913) and also H. S. Washington (*Prof. Paper, U.S. Geol. Surv.*, No. 99, 1917). Incidentally it may be remarked that there is no obvious objection to eliding the first " i " in Steininger's word, if in future it should prove useful to students of rock-types, magma-types, and the origin of basaltic melts.

The second reason for concern has to do with pronunciation—a trouble only partly lessened if " tholeyite " or " tholeite " were to be adopted for general use. I have not discovered any of the competing names in the New Oxford or any other complete British dictionary. " Tholeiite " does appear in the 1949 edition of Webster's New International Dictionary, published in the United States. There the proper pronunciation is given as " Tō′-lī-īt ", the editor evidently remembering that in German the " h " of the digraph " th " is silent. Thus there is some difficulty of pronunciation for a word intended for world-wide use, particularly evident if English-speaking and German-speaking petrographers, geologists, and geophysicists have to use it in *viva voce* discussions. One conceivable way to avoid such trouble in international debate on the different theories of the earth's basic shells and magmas would be to replace " tholeiite " by " palatinite ", the obsolete name coined by Laspeyres (1867) but re-defined as a basalt that is olivine-free in both norm and mode.

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HARVARD DEPARTMENT OF GEOLOGY,
CAMBRIDGE, MASSACHUSETTS.
15th December, 1951.

AGE OF THE PORTSALON CONGLOMERATE

SIR,—It is not quite clear what bearing Mr. Andrew's remarks (*Geological Magazine*, pp. 441–2) have on the question of a Torridon or Devonian date for the patch of red sediments and conglomerates near Portsalon. Either formation could equally well show sedimentary contact with and infiltration into an underlying metamorphosed quartzite of presumed pre-Torridon age. Mr. Andrews refers to the Geological Survey's early dating as based on " the very ' Old Red ' look of the sediments ". No doubt this was the case ; it seems to have been taken for granted without any particular comment in the records of the Geological Survey in Dublin.

There is in fact a noticeable difference between some of the Portsalon conglomerates and those of known Old Red, Carboniferous, and Triassic age elsewhere in Ireland :—the strong development of chloritic minerals in the matrix between the pebbles near Portsalon. (The writer exhibited a specimen of this rock at a meeting of the Geological Society in 1947.) This circumstance, as well as its geographical position, suggests that the possibility of a Torridonian age for this very isolated outlier should not be excluded. The nearest outcrops of Devonian rocks known to me are probably those at Fintona or Pomeroy in N. Ireland, over 50 miles from Portsalon and nearly as far from it as the Torridonian in Islay.

I have not had the opportunity of making a direct comparison between the Portsalon rock and the nearest Torridonian ; but it may well be that the metamorphic grade would give a clue to the age of these relatively undisturbed rocks of similar facies.

D. W. BISHOPP.

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CYPRUS.
31st December, 1951.

REVIEWS

GEOLOGIA APPLICATA ALL'INGEGNERIA. By ARDITO DESIO. pp. xxviii + 851, with 305 figs. Ulrico Hoepli, Milan, 1949.

Professor Desio, of the Geological Institute of Milan University, has written a book that is more than a textbook in the normal English or American sense. It is a well planned, adequately documented compendium, embracing in its scope the whole field of engineering geology, in the broadest interpretation of that term. In common with many Continental works written for the student, this book assumes no previous geological knowledge, and begins with a discussion of minerals and rocks, folding and faulting, the principles of stratigraphy, and geological maps. This is attempted in less than 100 pages and is necessarily the least contributive part of the book.

The second part, on applied hydrology, deals exhaustively with surface and ground water, and includes an interesting section on thermal mineral springs. A discussion on applied geomorphology follows, which deals with the engineering implications of physical geology. Such subjects as landslides, subsidence, river flooding, and coastal erosion are covered, and many examples are given. The fourth part concerns constructional geology, and treats of building stones, roads, canals, mines, dams, airports, and even cemeteries.

The final part strays beyond the field normally allotted to engineering geology and presents a summary survey of the occurrence of economic minerals. Magmatic and sedimentary ores and their secondary enrichment, coal, oil, and gas are included, together with a brief review of prospecting methods. So vast a subject can scarcely be dealt with, however rigorously, in the less than 200 pages allowed to it, although numerous references in the text to bibliographies at the end of each section point to detailed and world-wide sources for all the information summarized. These bibliographies are a valuable feature throughout the whole work.

The large numbers of line drawings, block diagrams, charts, and maps are particularly clear and helpful, but the half-tone photographic reproductions are poor. The book is clearly printed on fair quality paper and bound with the usual paper-back Continental binding. It contains an exhaustive index.

Italy is a country in which both civil and mining engineering are necessarily intimately connected with geology, and although examples are drawn from all parts of the world it is the Italian problems and points of view that reward the reader from other countries.

D. J. McL.

INTERNATIONAL GEOLOGICAL CONGRESS. Report of the Eighteenth Session, Great Britain, 1948. Part XIV : Proceedings of the Association des Services Géologiques Africains. London, 1951. (This Part of the Report, can be purchased separately, price 25*s*., post free, from Geological Survey and Museum, London.)

The volume is divided into three sections. The first of these is devoted to the proceedings of a series of open meetings of the Association, held during the Congress. It includes reports of discussions, both on papers presented to the Association and on other selected subjects ; in addition, it includes four annexes, dealing respectively with the work of the Commission for the International Geological Map of Africa, and with resolutions on the division of the African Pleistocene, the study of Stromatolites, and the Kalahari System. The second section consists of brief reports, specially requested by the Association, on the geology of certain African territories. The third section consists of personal communications, in which many and diverse aspects of African geology are discussed.

Of these contributions the " Regional Notes and Syntheses " of the second section will probably be of the widest general interest. It should be mentioned also that the personal communications include several which deal

with Rift Valley tectonics and one, by Professor Holmes, on Pre-Cambrian Orogenic Belts in South and Central Africa. Interesting discussions on both these subjects are reported in the first section. For the information of those who intend to be present at the next session of the Congress it should be noted that most of the papers on French North African geology are printed in abstract only. Nevertheless, those which are printed in full include a useful account, by M. Choubert, of the geology of the Anti-Atlas. In addition, there are various papers dealing with neighbouring territories. Two of these may be specially mentioned : M. Arnaud's report on recent discoveries in French West Africa and Sr. Desio's summary of the existing information on the geology of Libya.

R. W. H.

DAS POLARISATIONS-MIKROSKOP. By C. BURRI. Verlag Birkhaüser, Basel, 1950. pp. 308, 168 figs., 4 tables. Price 28.80 Swiss Fr. (unbound), 32.80 Swiss Fr. (bound).

This is an excellent textbook of crystal optics. An introductory section deals in detail with the nature of light and with the optical indicatrix. This is followed by sections on the microscope, on observations in ordinary light, on observations between crossed nicols, on pleochroism, on interference figures, on determination of refractive indices by immersion methods, and on the use of the universal stage. A final section treats of the determination of extinction angles for faces and zones of biaxial crystals. In each section both the theory and practice of the methods used are clearly described. The book is well illustrated and well printed. It is a pity that no English edition is available for students.

S. R. N.

SPECTROCHEMICAL ANALYSIS. By L. H. AHRENS. Addison-Wesley Press, Inc., Cambridge, Mass., 1950. pp. xxiv + 338, 4 plates + 52 text-figs. Price $10.

Although primarily intended as a textbook for spectrographers concerned with the D.C. arc analysis of minerals, this book should prove of interest to many geologists. In Part I they will find full and clear details of the methods for qualitative, semi-quantitative, and quantitative determination of trace constituents. In Part II the individual elements are considered and data given for each on choice of line, sensitivity, ease of determination in different kinds of material and, in many cases, facts about distribution with references for further reading. A final chapter considers the spectrographic determination of the major constituents of rocks and minerals. There is a bibliography with some 450 entries, and useful wavelength tables of the most sensitive lines of the elements in the arc.

S. R. N.

CROWN AGENTS FOR THE COLONIES

Prospector required by the Government of Sierra Leone for the Geological Survey Department for a tour of 18 to 24 months in the first instance. Salary (including allowances) either £808 or £875 a year according to age. Gratuity of £25 for each 3 months' service on satisfactory completion of engagement. Outfit allowance £60. Free passages. Liberal leave on full salary. Candidates should have had previous experience of Pre-Cambrian Terrains and be prepared to remain for long periods in the bush. They must be able to supervise deep trenching and pitting : sharpen hand drills and do simple blacksmithing ; train hand drillers ; blast and train blasters ; drive winze and rise in field conditions ; make small simple windlasses ; splice wire and vegetable fibre ropes ; recognize commoner economic minerals ; pan and trace outcrops by loaming and following float ; take rough samples and estimate valuable contents by panning ; read simple maps and use a compass.

Apply at once by letter, stating age, full names in block letters, and full particulars of qualifications and experience, and mentioning this periodical, to the Crown Agents for the Colonies, 4 Millbank, London, S.W. 1, quoting on letter M.27797.E. The Crown Agents cannot undertake to acknowledge all applications, and will communicate only with applicants selected for further consideration.

HIS MAJESTY'S COLONIAL SERVICE

Applications are invited for the following post :—

Experimental Officer, Mineral Resources (Research) Committee (27079/60/51) Uganda. Appointment on contract for 2½ to 3 years in the first instance. Salary, according to qualifications and experience, in the scale £550 to £1,320 plus a temporary allowance of 20 per cent of salary subject to a maximum of £200. A gratuity of 15 per cent of nine tenths of basic salary will be paid on satisfactory completion of contract. Outfit allowance of £30 payable on first appointment. Rent for partly furnished Government quarters 10 per cent of salary (unfurnished 7½ per cent). Free passages provided for officer and family up to cost of 3 adult passages. Income Tax at low East African rates, Non-Native Poll Tax and Non-Native Education Tax payable. Five days' vacation leave on full salary for each completed month of resident service. Candidates, preferably under 30 years of age, should possess a pass degree in Geology, Physics, Mining, or Mining Geology or Associateship of the Royal School of Mines. Duties, which would necessarily entail living under camp conditions for much of the time, consist of carrying out detailed examinations of mineral deposits of specific areas ; surveying and laying out prospecting areas, road clearing, camp building, etc. ; collation of records and assisting Geologists and Geophysicists in handling of instruments, etc.

Intending candidates should apply in writing to the Director of Recruitment (Colonial Service), Colonial Office, Sanctuary Buildings, Great Smith Street, S.W. 1, giving brief details of their age, qualifications, and experience. They should mention this periodical and quote the reference number (27079/60/51).